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MECHANICAL FASTENING OF NICKEL-BASE ALLOYS

By D. L. Cheever, R. E. Monroe, and D. C. Martin

Prepared Under the Supervision of the
Research Branch, Redstone Scientific Information Center
Directorate of Research and Development
U. S. Army Missile Command
Redstone Arsenal, Alabama

NASA

George C. Marshall Space Flight Center, Huntsville, Alabama

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ABSTRACT

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This report covers the state of the art of mechanical fastening of nickel-base alloys. The designing, forming, machining, assembling, and inspection of nickel-base joints are described in detail when the processes used are known to differ markedly from those processes used for common steel, aluminum, and copper alloys.

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PREFACE

This report is one of a series of state-of-the-art reports being prepared by Battelle Memorial Institute, Columbus, Ohio, under Contract No. DA-01-021-AMC-11651(Z), in the general field of materials fabrication.

This report is primarily intended for design and manufacturing engineers. It reviews the information available on the mechanical fastening of nickel-base alloys. The mechanical fastener, the parts being joined, or all of the parts in the joint may be made of a nickel-base alloy. According to available information, experience with mechanically fastened joints composed of nickel-base alloys is neither widespread nor well developed. Consequently, this report surveys only those aspects of mechanically fastening nickel-base alloys that differ markedly from the fastening of steel, aluminum, or copper alloys. It is assumed that the reader is acquainted with or has access to the large amount of literature available that deals with standard design practices, selection of mechanical fasteners, assembly of joints, and all other considerations necessary when mechanically fastening the more common materials.

An extensive search for information was conducted by examining references extending back to 1958. In addition to a literature search, a review was made of the trade information available from manufacturers of nickel-base fasteners.

In accumulating the information for this report, the Main Library, the Slavic Library, the Defense Metals Information Center, and the Fasteners Research Council Technical Abstracts within Battelle were searched back to 1958. Outside Battelle, the Defense Documentation Center and the Redstone Scientific Information Center were searched.

The authors acknowledge the help of Vernon W. Ellzey and Albert G. Imgram of Battelle, Project Technical Coordinators, and Walter Veazie, Battelle Information Specialist.

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MECHANICAL FASTENING OF NICKEL-BASE ALLOYS

SUMMARY

Nickel-base alloys are primarily used in applications where corrosion resistance, particularly to caustic environments, or high-strength properties at elevated temperatures are desired. Nickel-base materials are sometimes used at cryogenic temperatures. They also are used because of their unusual or outstanding physical properties. The unique properties of the nickel-base alloys require procedures for fabricating mechanically fastened joints that differ from the ordinary procedures used for mechanically fastening more common structural materials. Fabrication of mechanically fastened joints using nickel-base alloys can be an expensive operation because the material costs are high, the machining rates are low, and the materials must be carefully cleaned for most applications.

Considerations used in the selection of mechanical fasteners made from nickel-base alloys differ very little from those used in the selection of fasteners made from more common materials. The difficulties that have been encountered during the fabrication of mechanically fastened joints in nickel-base alloys are reviewed along with successful solutions. Reliable mechanically fastened joints composed of nickel-base alloys can be fabricated readily with minimum difficulty if design and fabrication of the joint utilize previously developed procedures.

INTRODUCTION

Nickel-base alloys have been used primarily in mechanically fastened* joints where high corrosion resistance or high-strength properties at elevated temperatures are desired. Nickel-base alloys have shown a marked superiority for handling sodium hydroxide at temperatures up to 900 F (Ref. 1). The ultimate tensile strength of

*Two terms that are quite similar have special meanings within this report and are defined here to avoid confusion. The terms are "fastener" and "fastening". A fastener is a specific mechanical device that mechanically joins two or more parts to form a joint. Fastening is a process only, and generally requires the use of mechanical fasteners. The end result is a mechanically fastened joint.

nickel-base alloys can range from 140 to 200 ksi at 1200 F and from 90 to 110 ksi at 1600 F (Ref. 2). Dispersion-hardened nickel materials have usable strength up to temperatures of 2000 F. Nickel-base materials also are sometimes used down to liquid-hydrogen temperatures. In addition, some nickel-base alloys are used because they possess unusual physical properties or unusual combinations of properties.

The five basic methods of joining metals are:

(1) Mechanical fastening
(2) Adhesive bonding
(3) Welding
(4) Brazing
(5) Soldering.

Each of these joining methods has comparative advantages in specific applications. For example, mechanically fastened joints can be rapidly inspected visually and nondestructively for any defects in the total component. A number of mechanical fasteners can be disassembled for inspection or accessibility and then can be reused. Comparative disadvantages exist for each joining method in specific applications, too. A gasket or sealant is generally required in mechanically fastened joints to produce leaktight joints. The need for the sealant and the temperature limitations of the sealant make the use of mechanically fastened joints undesirable in some applications. Mechanically fastened joints are generally bulkier and heavier than joints made by other methods. For additional information on the other methods of joining nickel-base alloys, consult the Redstone Scientific Information Center reports on adhesive bonding by Keith, Monroe, and Martin (Ref. 3), and welding, brazing, and soldering by Vagi, Monroe, and Martin (Ref. 4).

This report has been prepared for design and manufacturing engineers and, thus, presumes that the reader has some knowledge about mechanical fastening of common materials. The specific aspects of mechanical fastening of nickel-base alloys are detailed when the techniques or procedures are markedly different from those used for mechanically fastening common materials.

NICKEL-BASE ALLOYS

Olofson, Gurklis, and Boulger (Ref. 5) have separated nickel alloys into commercially pure nickel, Monel alloys, and high temperature or superalloys. They further subdivided the alloys into groups characterized by similar composition and machinability as shown in Figure 1. Table I lists the compositions of the nickel-base alloys discussed within this report.

TABLE I. COMPOSITION OF SELECTED NICKEL-BASE ALLOYS[(a)]

Alloy	Composition, per cent by weight							
	Ni	Cr	Co	Mo	Ti	Al	C	Other Elements
Inconel X-750	70	15	-	-	2.5	0.7	-	7Fe, 1.0Cb, 0.65Mn
Inconel 700	48	15	28	3	2.5	2.5	0.10	1.0Mn, 1.0Fe
Inconel 718	50-55	17-21	-	3	0.8	0.5	0.10[(b)]	5Cb, bal Fe
Waspaloy	59	19.5	13.5	4.2	2.5	1.2	0.07	1Mn, 2Fe
René 41	55	19	11	10	3	1.5	0.12	--
Udimet 500	Balance	15-20	13-20	3-5	2.5-3.2	2.5-3.2	0.15[(b)]	--
Udimet 630	Balance	17.5	-	2.9	1.0	-	0.04	2.75W, 17.2Fe, 6.2Cb and Ta
Udimet 700	Balance	13-17	17-20	4.5-5.7	3-4	3.7-4.7	0.15[(b)]	0.1B
Incoloy 901	43	12.8	-	5.7	2.4	-	0.05	35Fe
Hastelloy R-235	60	15.5	2.5	5.5	2.5	2	0.16	1.0Si, 10Fe, 1Mn,
Udimet 600	50	17.5	16.5	4	3	4.2	0.10	4Fe
M-252 (J-1500) René 62	55	20	10	10	3	1	0.15	--
AF 1753	Balance	16.6	7.5	1.6	3.0	2.0	0.20	8.5W, 8.6Fe
D979	45	15	-	3.75	3	1	0.05	0.5Mn, 0.5Si, 27Fe, 3.75W, 0.01B
Nickel 270	99.97	-	-	-	-	-	-	--
Nickel 201	99.6	-	-	-	-	-	0.01	--

(a) These compositions were obtained primarily from References (2) and (6). Most alloy compositions are available in ranges that can be obtained from the supplier.
(b) Maximum.

PROPERTIES

A large amount of nickel-base-alloy data has been assembled (Ref. 2) primarily from trade literature and is presented in the following tables and figures. Table II gives typical room-temperature

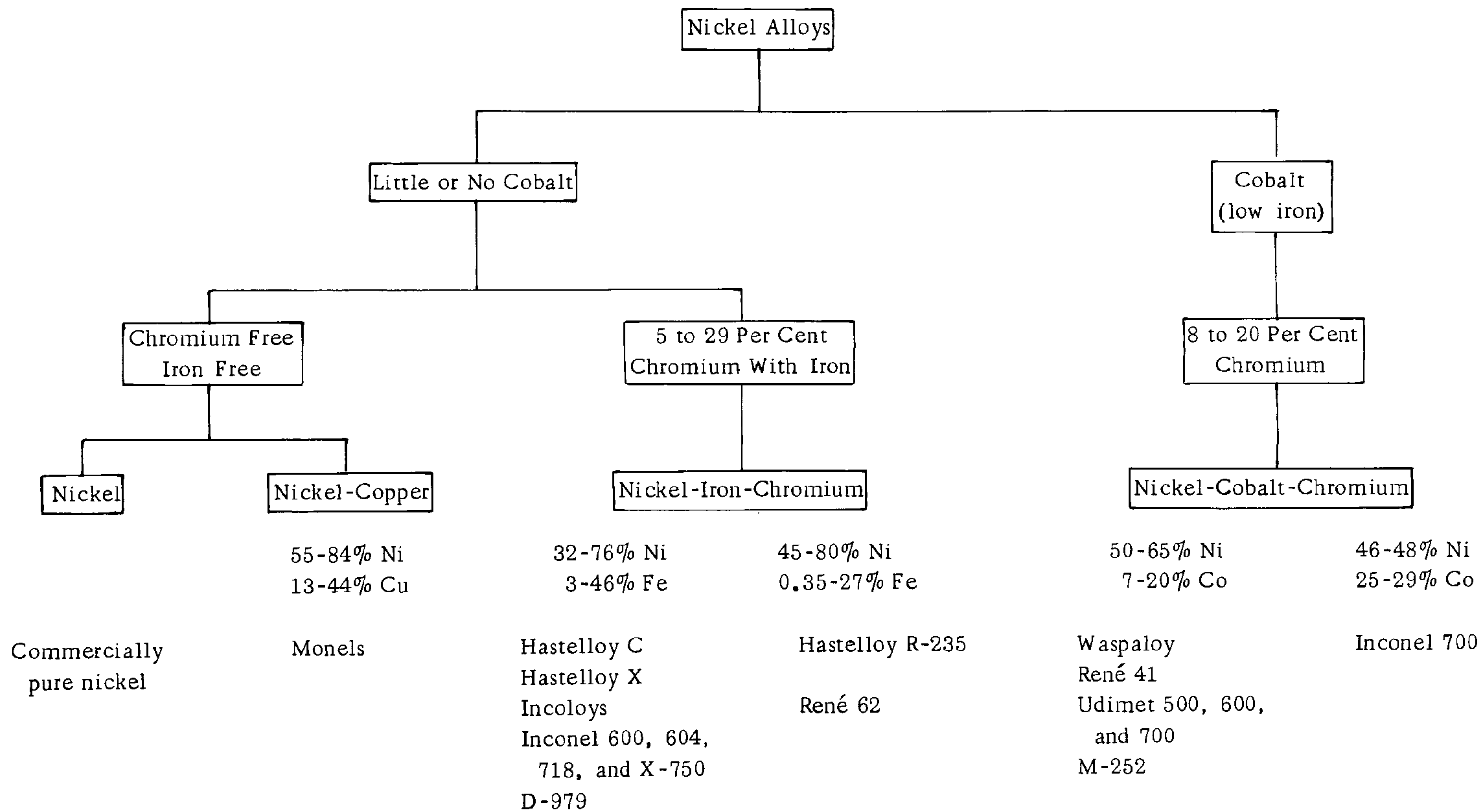


FIGURE 1. GENERAL CLASSIFICATION OF SELECTED NICKEL-BASE ALLOYS (REF. 5)

TABLE II. MECHANICAL PROPERTIES OF SELECTED NICKEL-BASE ALLOYS AT ROOM TEMPERATURE (REFS. 7, 8)

Alloy	Ultimate Tensile Strength, ksi	Yield Strength, ksi	Elongation, per cent	Thermal Conductivity, Btu /hr ft^2 °F
Inconel 700	171	104	25	7
Inconel 718	145-196	120-150	10-25	--
Waspaloy	180	115	28	6.5
René 41	185-206	148-154	9-14	5
Udimet 500	190	130	18	6.5
Udimet 630	190	150-180	25	--
Udimet 700	204	140	17	11
Incoloy 901	166-175	107-130	23	--
Hastelloy X	104-108	49-51	46-50	5
Hastelloy R-235	141-159	57-79	30-49	--
Udimet 600	190-235	132-200	10-13	--
M-252	123-180	61-122	20-55	--
René 62	205	160	7	--
AF 1753	--	--	--	--
D-979	195-204	134-146	14-15	--
Nickel 270	52	--	55	--
Nickel 201	56-100	21-90	10-45	--

Note: These values are dependent upon the material form and prior treatment.
All points where data are unknown are marked with a dash.

properties of the alloys' compositions given in Table I. Figure 2 shows the variation of ultimate tensile strength with temperature for bar stock. Figure 3 shows the variation of ultimate tensile strength with temperature for sheet. Figure 4 illustrates the variation of 0.2% yield strength with temperature for sheet. Figure 5 gives the variation of 100-hour creep-rupture strength with temperature for sheet.

The density of nickel-base alloys is about 0.29 lb/in.^{3} as compared with 0.29 for steel alloys, 0.16 for titanium alloys, and 0.10 for aluminum alloys. The modulus of elasticity at room temperature is about the same for nickel-base alloys as for steel alloys, 30,000 ksi. The variation of the coefficient of thermal expansion with temperature for a number of nickel-base alloys is shown in Figure 6. The thermal conductivity of nickel-base alloys is generally 90 Btu in./ft^2 hr °F in. at room temperature and about 160 Btu in./ft^2 hr °F in. at 1600 F. The thermal conductivity of Inconel X-750 is significantly greater than most of the nickel-base alloys: 258 Btu/ft^2 hr °F in. at 1600 F (Ref. 2). Johnson (Ref. 2) has compiled a comprehensive listing of physical properties for 13 nickel-base alloys. DMIC Report 132 (Ref. 9) provides data on the mechanical and physical properties of 18 nickel-base alloys.

CORROSION

Nickel-base alloys are widely used for corrosion resistance to seawater, to hydrochloric acid, and to sodium hydroxide at temperatures up to 900 F (Ref. 1). Caution should be taken when specifying the nickel-base alloys for corrosion resistance. Like copper alloys, the corrosion resistance of nickel-base alloys decreases as the amount of oxygen present increases, particularly in acidic environments (Ref. 1). Two primary forms of corrosion should be considered before nickel-base materials are specified in designs.

Galvanic Corrosion. Galvanic corrosion or two-metal corrosion is a serious problem when the fastener and the pieces being joined are made of dissimilar metals. A galvanic series for various metals based upon work with seawater environments is given:

Magnesium	Brass
Zinc	Copper
Aluminum	Monel
Cadmium	Nickel (passive)
Steel and iron	Inconel (passive)
304 stainless steel (active)	304 stainless steel (passive)
Hastelloy C	Silver
Nickel (active)	Gold
Inconel (active)	Platinum

When one metal is placed in electrical contact with another in seawater, the metal closer to magnesium will be the anode and will be attacked while the other metal will act as the cathode and will not be attacked. The farther apart two metals are on this list, the greater the rate of attack will be.

The series also shows that brass, copper, stainless steel, and silver alloys could be expected to have a small rate of attack when used with nickel-base alloys. Magnesium, zinc, aluminum, and cadmium alloys are not at all compatible with nickel-base alloys. Use of fasteners made of these alloys should be avoided not only because of their separation on the galvanic scale but also because of their unfavorable anode to cathode area ratio. When the cathode to anode surface area ratio is much greater than unity, as it would be for

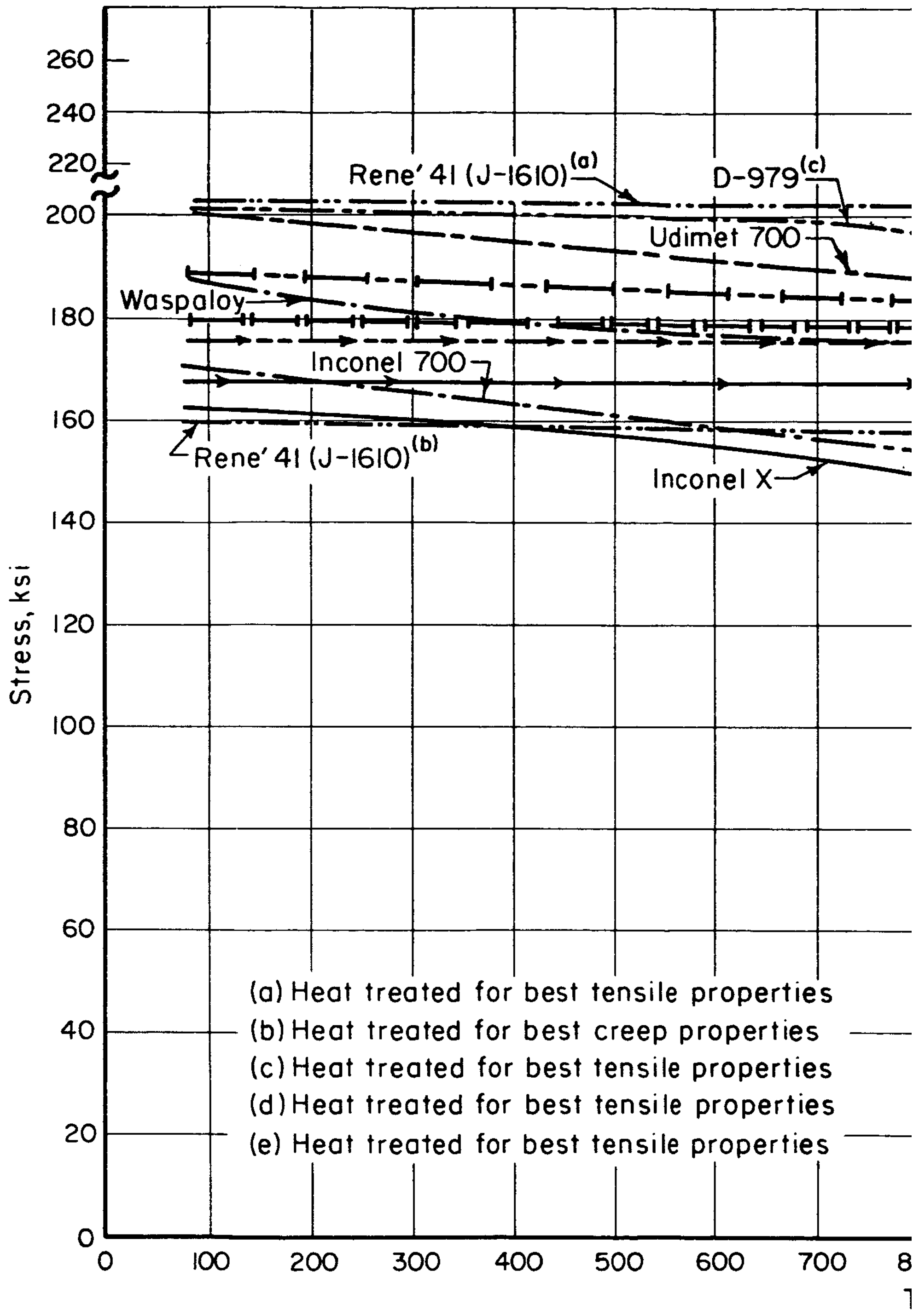
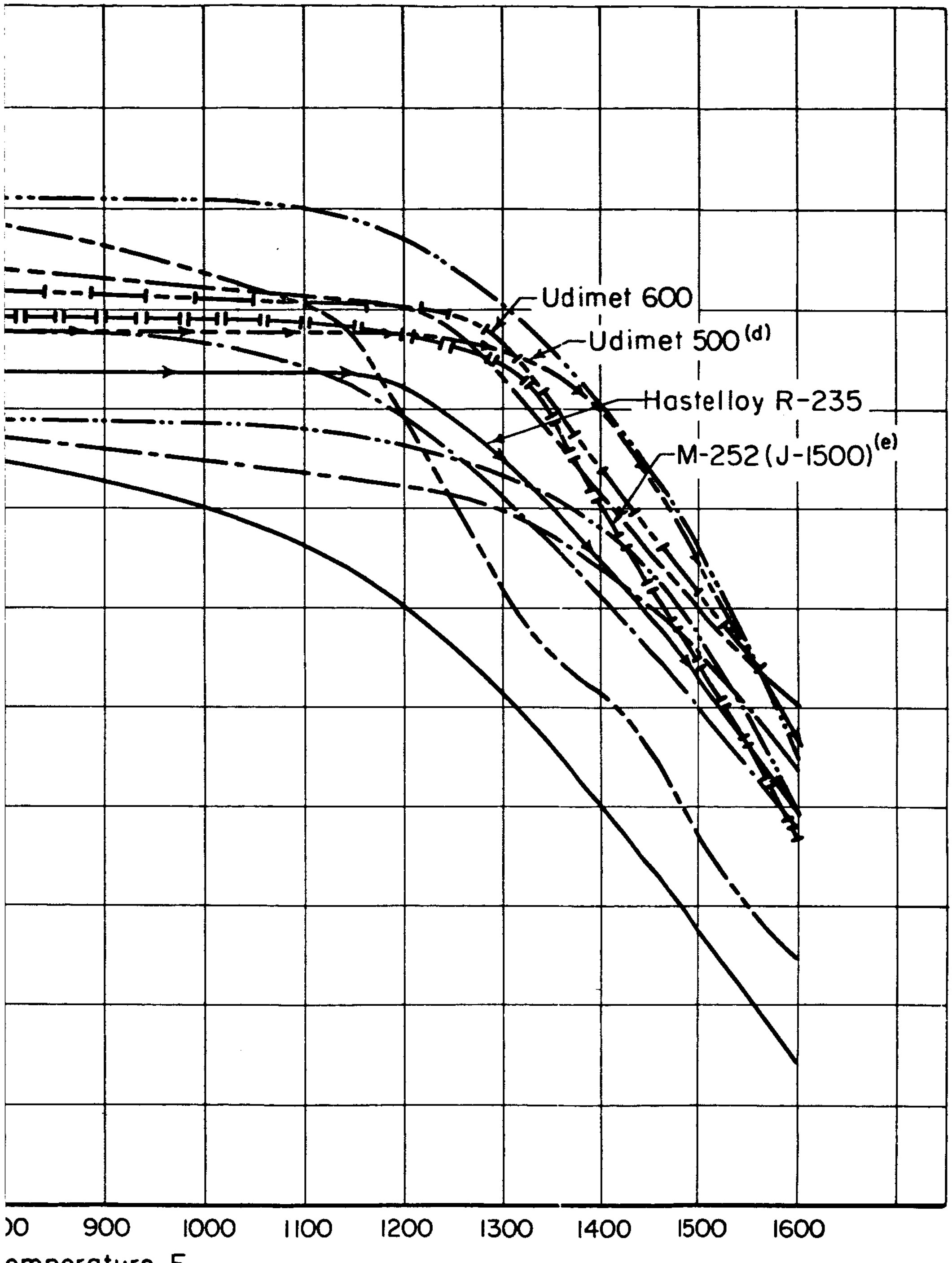


FIGURE 2. VARIATION OF ULTIMATE TENSILE STRENGT
TEMPERATURE FOR BAR (REF. 2)

10



Udimet 600
Udimet 500(d)
Hastelloy R-235
M-252 (J-1500)(e)
00
900
1000
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1300
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1600
emperature, F

H WITH

82

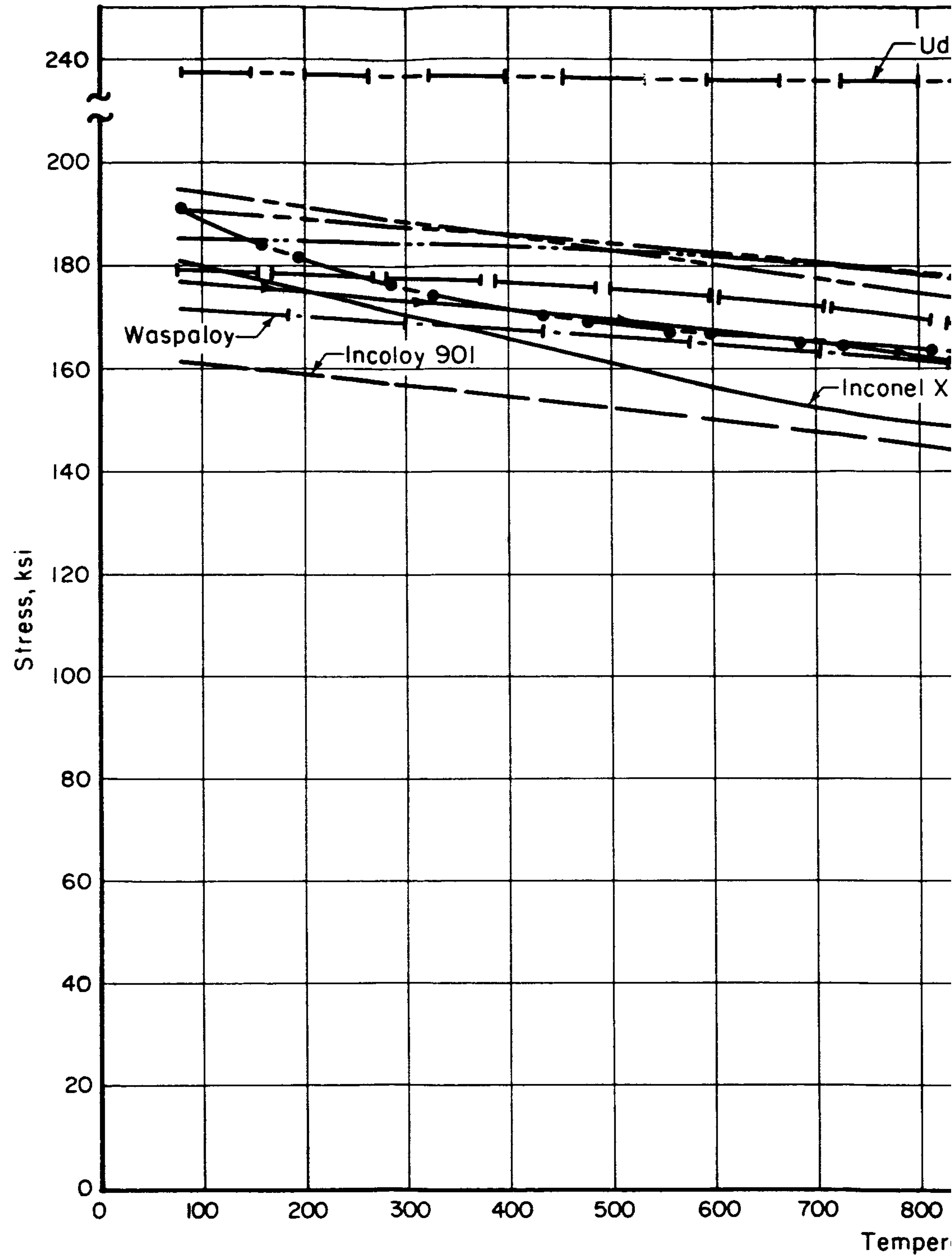
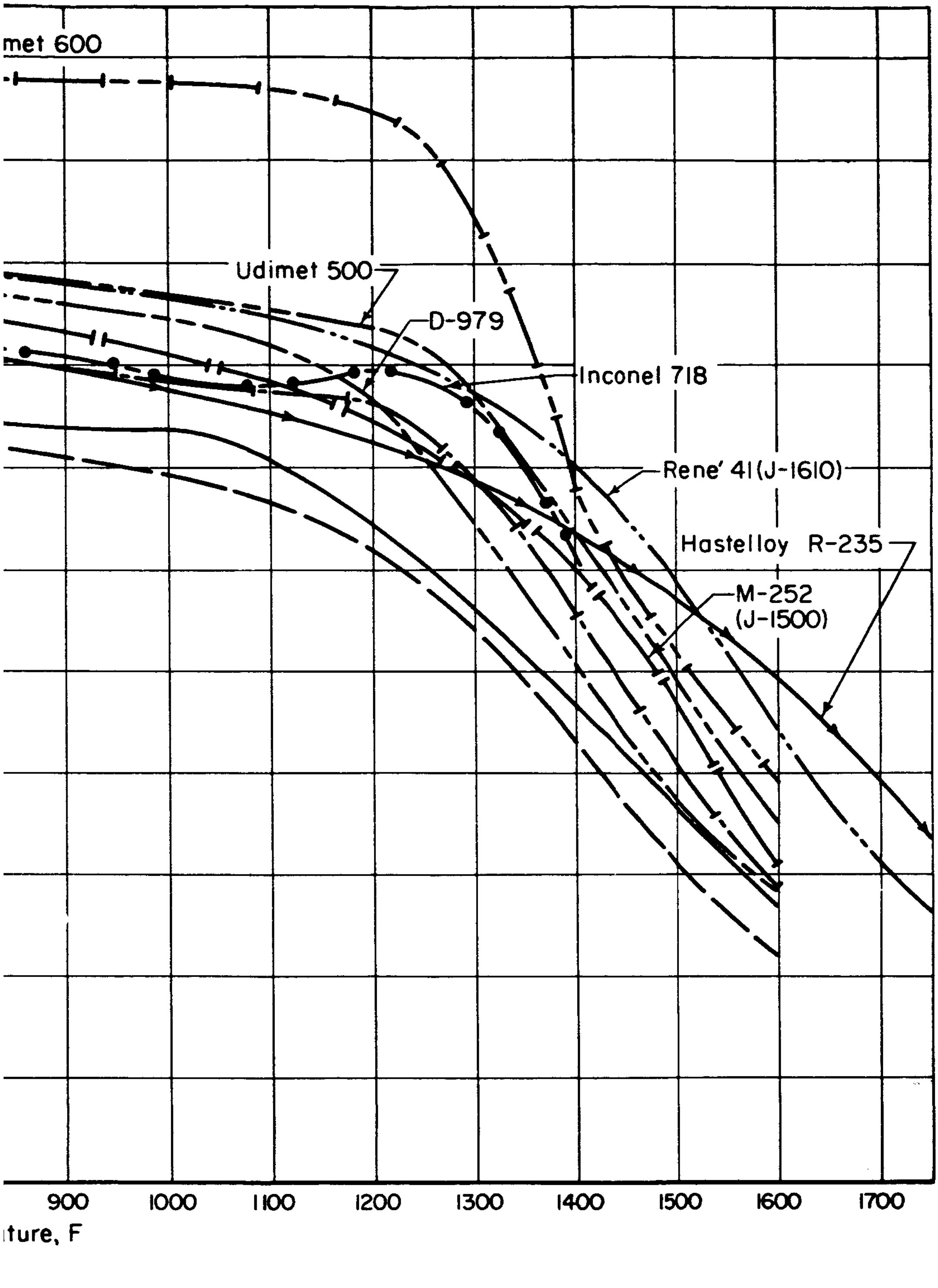


FIGURE 3. VARIATION OF ULTIMATE TENSILE STRENGTH WI
TEMPERATURE FOR SHEET (REF. 2)

9(1)



met 600
Udimet 500
D-979
Inconel 718
Rene' 41(J-1610)
Hastelloy R-235
M-252
(J-1500)
900
1000
1100
1200
1300
1400
1500
1600
1700
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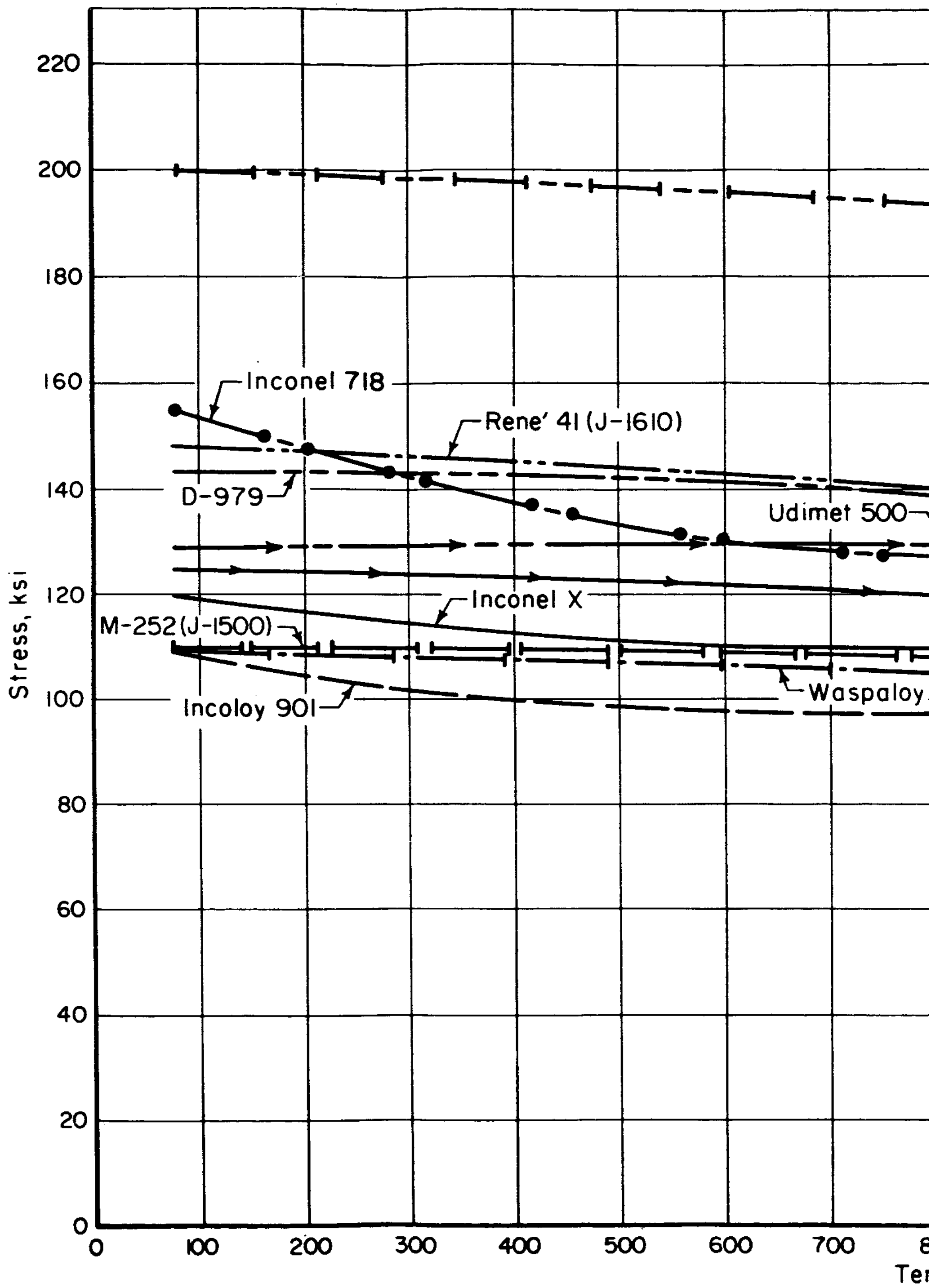
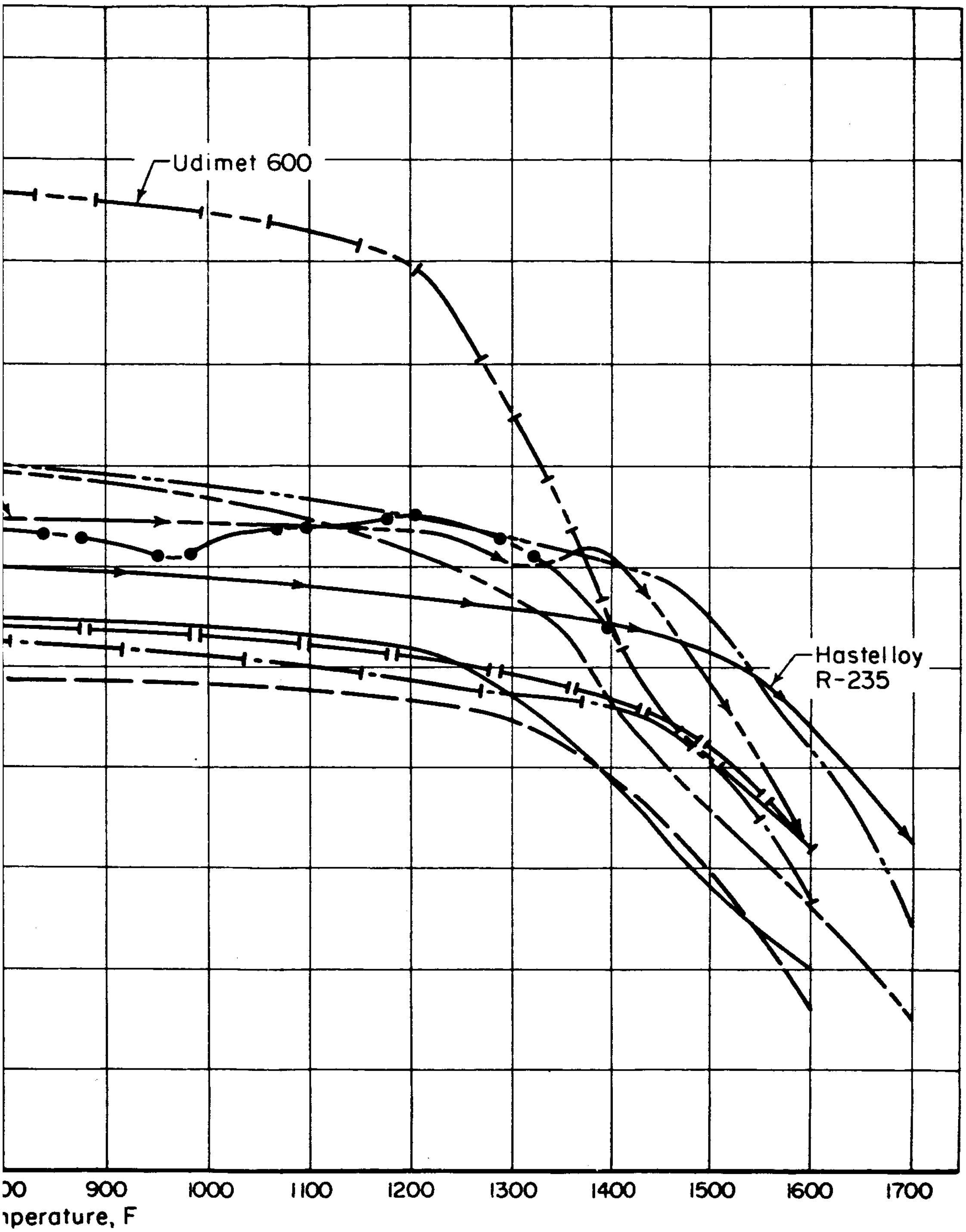


FIGURE 4. VARIATION OF 0.2 PER CENT YIELD STRENG
FOR SHEET (REF. 2)

11 D



Udimet 600
Hastelloy
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00
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TH

12 (2)

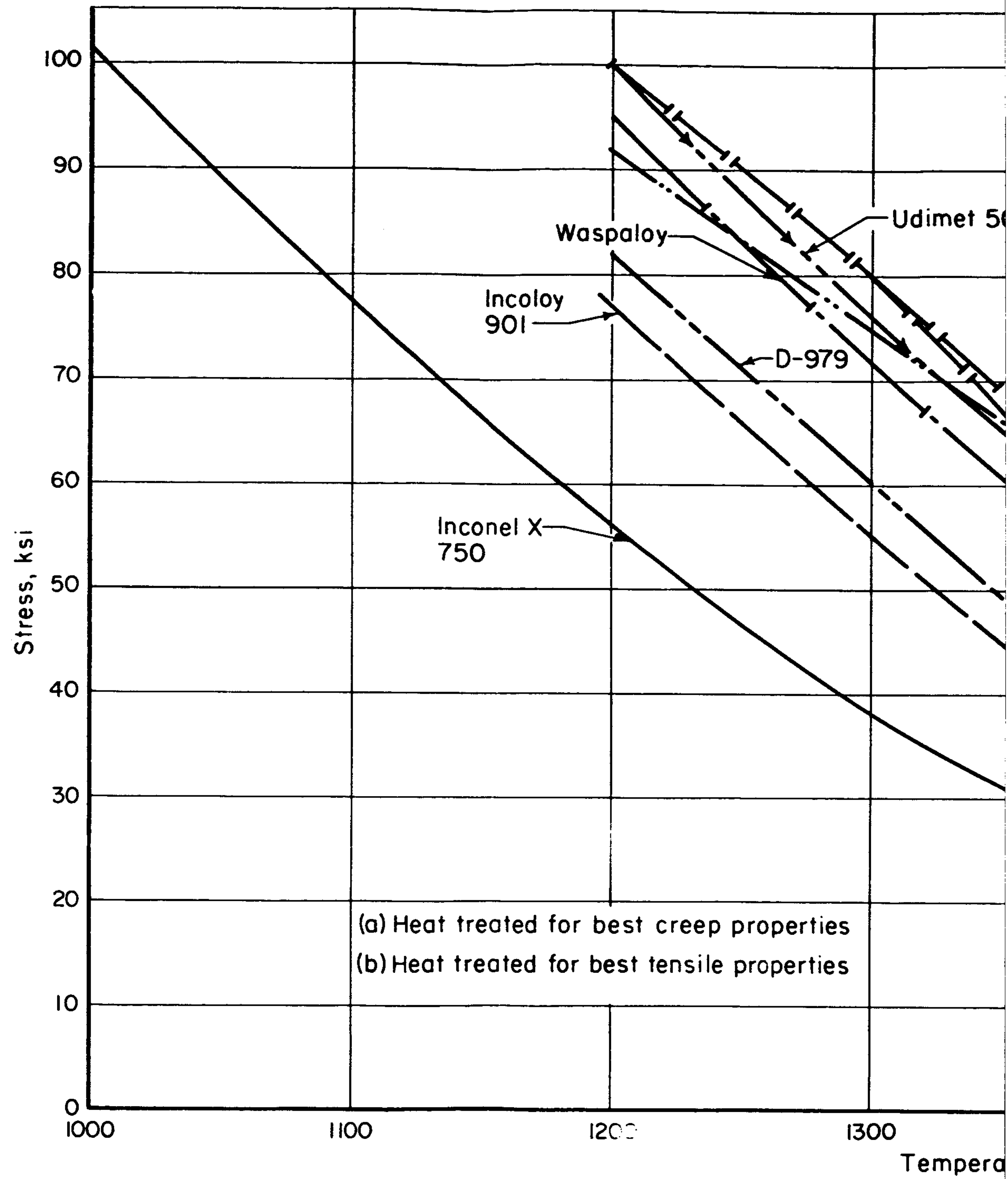
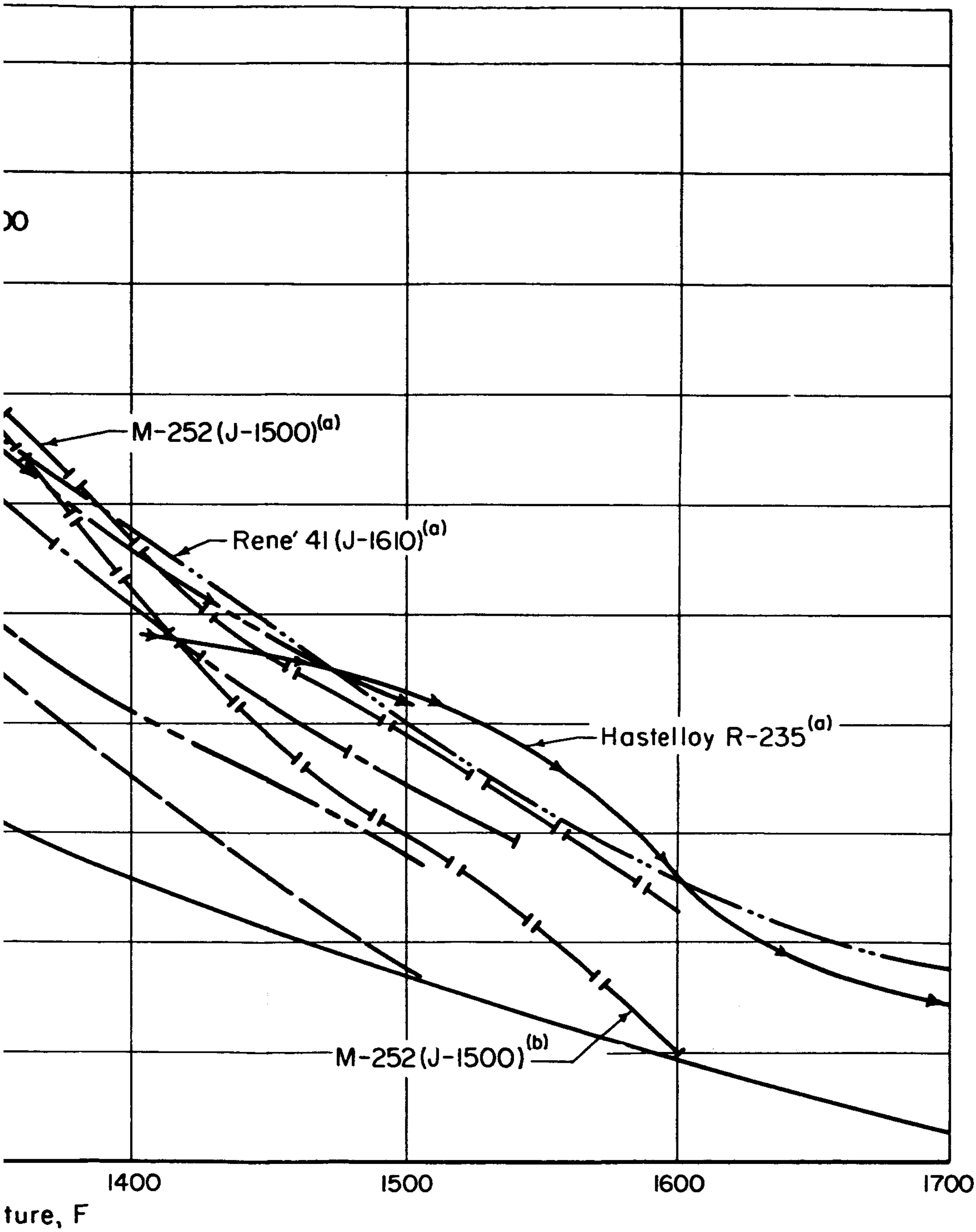


FIGURE 5. VARIATION OF 100-HOUR CREEP-RUPTURE STRENGTH WITH TEMPERATURE FOR SHEET (REF. 2)

13 (1)



)0
M-252 (J-1500)(a)
Rene' 41 (J-1610)(a)
Hastelloy R-235(a)
M-252 (J-1500)(b)
1400
1500
1600
1700
ture, F

2

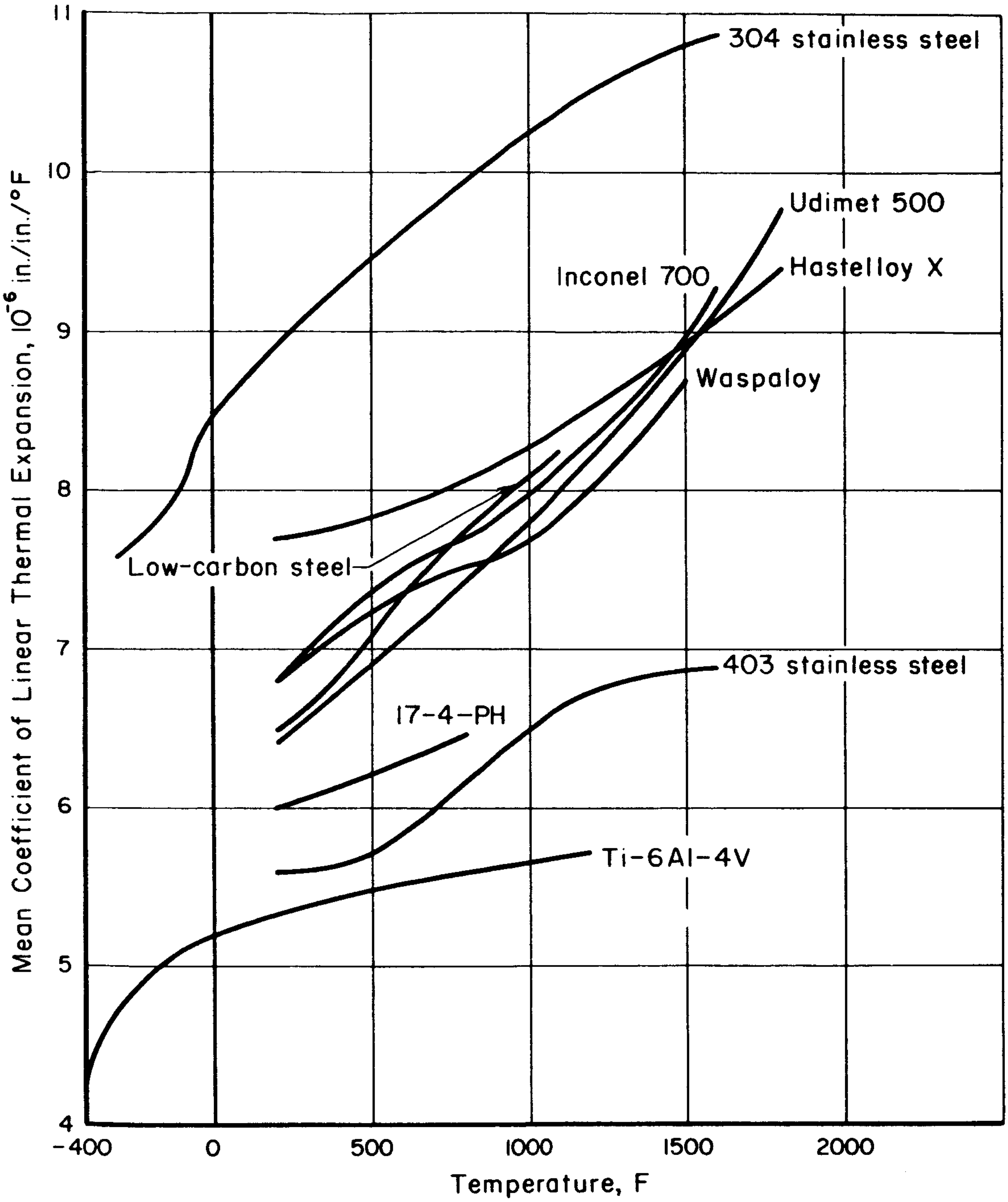


FIGURE 6. VARIATION OF COEFFICIENT OF THERMAL EXPANSION WITH TEMPERATURE FOR A NUMBER OF MATERIALS (REF. 7)

magnesium, zinc, aluminum, or cadmium fasteners in nickel-base sheet, the rate of attack is greatly increased. All designs should have a low ratio of the cathode to anode area.

Grain-Boundary and Liquid-Metal Corrosion. Very small changes in temperature greatly decrease the corrosion resistance of most materials in corrosive environments. Any material used at high temperatures or heated to a high temperature during fabrication can be seriously corroded by environments that are not normally corrosive at room temperature.

Nickel-base alloys are more susceptible to sulfur embrittlement than most other materials (Ref. 9). Any sulfur containing grease, oil, cutting lubricant, paint, etc., must be removed from the alloys prior to exposure to high temperatures. A degreasing and chemical cleaning procedure, such as that described in the section on forming, is necessary to remove completely any contaminants. Mechanical abrasion is not satisfactory.

Small particles of lead- or zinc-alloy dies are sufficient to cause catastrophic attack of nickel-base parts (Ref. 10). These particles must be removed by appropriate cleaning operations. Attack by lead is the most severe. In one case, lead completely penetrated a 0.03-inch-thick nickel alloy after heating it to 1975 F for 30 minutes. Aluminum attacks René 41 less severely than lead, and zinc-base alloys cause the least severe attack. The corrosive effect of these materials is caused by the destruction of the protective surface layer on René 41. For example, lead apparently destroys the protective surface film as rapidly as it is produced at 1975 F. The result is a spongy, oxygen-rich, lead-nickel product of low density and with poor mechanical properties. Apparently, attack is initiated at the grain boundaries. At 1400 F, aluminum is more corrosive than lead. As the temperature is reduced toward the melting points of the contaminants, the amount of attack decreases. Below the melting point of the contaminants, attack ceases altogether.

Precautions. When nickel-base alloys are heated during fabrication or service, three precautions should be observed:

(1) Standard cleaning operations should be used that thoroughly remove sulfur-containing paints, lubricants, or greases. The cleaning operations should also remove, as much as possible, any alloys of lead, aluminum, magnesium, or zinc. The cleaning operations should be completed immediately before exposure to high temperatures. Careful

handling procedures should be used both during and after cleaning.

(2) Sulfur-containing materials should be avoided whenever possible. Sulfochlorinated cutting lubricants, which are used to improve machining rates with nickel-base alloys, also should be avoided. Chlorinated cutting oils are a good substitute.

(3) All metal brought into contact with nickel-base alloys such as in forming or clamping should be metals other than lead, aluminum, zinc, magnesium, tin, and their alloys (Ref. 10).

JOINT DESIGN

Mechanically fastened joints are made in a variety of ways. Besides the familiar riveted and bolted joints, mechanical joints may be shrink fitted or held together by keys or snap fasteners. In gas turbines, "fir-tree" joints are common fasteners for mechanically fastening turbine blades to turbine wheels. In this report, attention is given to joints made with through fasteners such as rivets, bolts, and screws.

As for any other material, the considerations made during the design of a component determine the production rate and reliability of the finished product. This section considers design details that are significant in most structures.

JOINT SELECTION

Figure 7 illustrates the basic joint designs that are used with mechanical fasteners. Multiple row, blind riveted, and the many other forms of joints used in production are all made up of one or more of the basic joint types shown. The joint configuration is chosen to meet the service conditions. Twelve basic factors to consider when designing mechanically fastened joints and selecting materials are as follows:

(1) Weight
(2) Accessibility
(3) Equipment
(4) Assembly
(5) Inspection
(6) Reusability
(7) Surface contour
(8) Electrical conductivity
(9) Corrosion
(10) Sealing
(11) Stress concentration
(12) Galling.

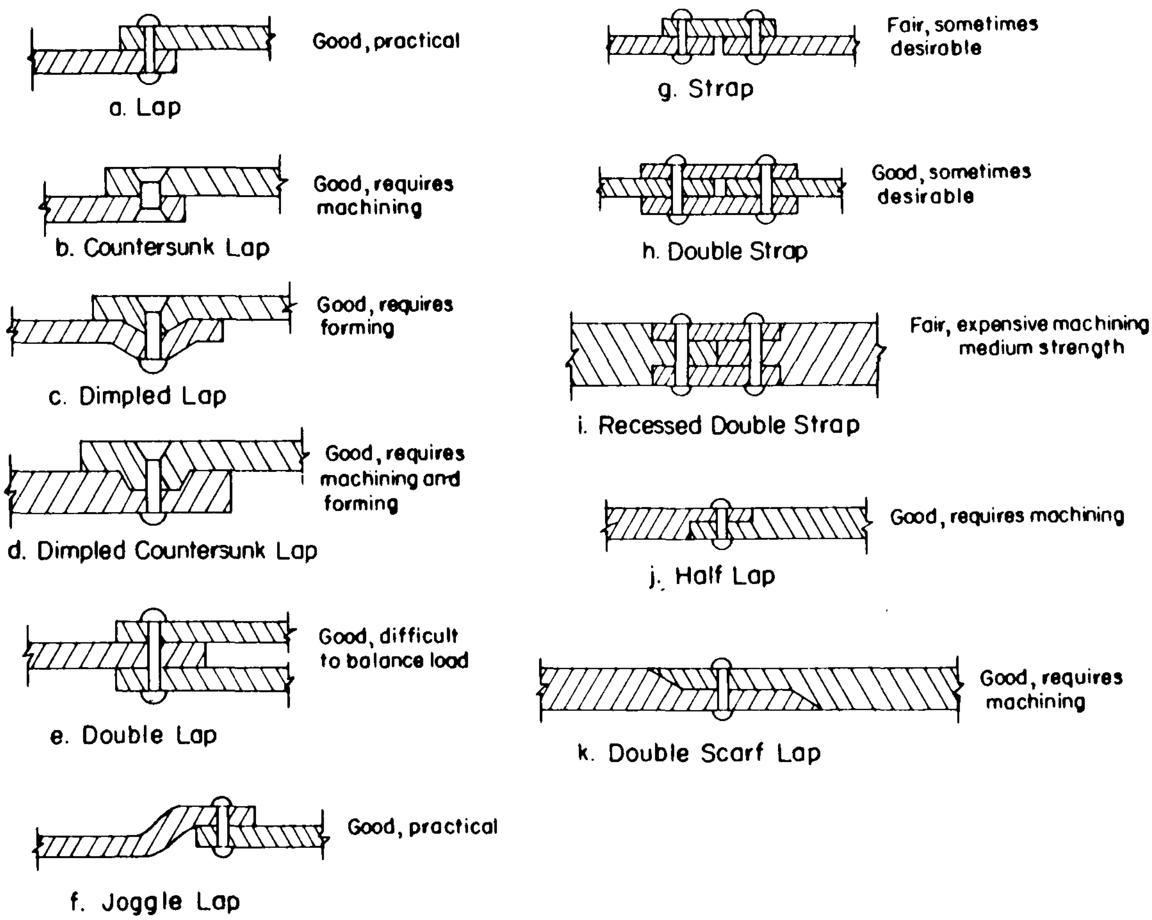


FIGURE 7. BASIC JOINT DESIGNS

Weight. Mechanically fastened joints are generally heavier than joints of equal strength produced by other joining methods. Where light weight is a prime consideration, careful calculations and tests should be undertaken to achieve optimum weight in the joint and the fasteners for the design strength. Fasteners with high strength-to-weight ratios have been used in applications requiring minimum weight.

Accessibility. Fasteners in a joint must be placed at points where they are fully accessible to the driving or tightening tool. Inspection or access panels should be designed so that the panels are readily removed and the fasteners are easily replaced if they become damaged or worn.

Equipment. The joint design selected and the fastener used are dependent upon the equipment available for fabrication. A shop that does not have the equipment or setup for dimpling nickel-base alloys may be able to machine countersunk holes to achieve smooth-surfaced joints. The type of equipment used determines the conditions necessary for complete accessibility during assembly.

Assembly. Mechanically fastened joints can be designed for easy assembly. The components can be set up in tooling, and the machining necessary for the mechanical fasteners is then performed. Generally, after drilling holes in nickel-base alloys, the components must be deburred and cleaned before final assembly. Mechanically fastened joints can be drawn together by the fasteners during the final assembly. This capability does not require exact fitup or elaborate fixtures during the final assembly stages.

Inspection. Mechanically fastened joints can be given a thorough nondestructive inspection after final assembly. Visual inspection can locate defective or loose fasteners if the joints are designed properly. Accessibility to both sides of a joint after assembly is desirable. If the tightness of the fasteners is to be checked, the joints should be designed to allow complete and easy access for testing tools.

Reusability. Mechanical fastenings are frequently employed because some specific fasteners allow nondestructive disassembly of a joint for access, inspection, or maintenance. Frequent disassembly of joints is inevitably accompanied by wear and damage. The components of such a joint should be designed for ready replacement. If preloaded bolts are used, they should not be torqued to a stress high enough to cause permanent deformation of the fastener or joint after a short period of service. Permanent deformation of the fastener would not only make the fastener unusable after removal, but would make disassembly slow and possibly cause damage to the joint. The fastener and the joint materials should be selected to avoid galling (cold welding) because this makes a joint difficult to disassemble and limits the reusability of the fastener.

Surface Contour. In aerospace applications, a smooth contour is necessary for aerodynamic efficiency. In chemical industries, a smooth contour is necessary for thorough cleaning. Smooth joints are achieved by the use of countersunk head fasteners and dimpled or countersunk holes. Some fasteners are shaved level with the plate surface after assembly. Fasteners that are level with the sheet surface can cause a waviness in thin-sheet structures that is unacceptable in some situations.

Electrical Conductivity. Unless carefully insulated, a mechanically fastened joint is an excellent conductor of electricity. In applications where the entire structure is grounded, high electrical conductivity is desirable. Organic or inorganic insulators are used in applications where one side of the joint must be electrically isolated from the other or where electrical contact between dissimilar metals is avoided to prevent corrosion. In insulated joints, the fasteners must be designed to avoid direct contact with the metal both on the surfaces of the joint and along the length of the fastener. Generally, an organic insulator is used that has a temperature limitation far below that of the high-temperature service applications of most nickel-base alloys. Inorganic insulators are available, but they are brittle and may fail if they are not loaded uniformly. Inorganic insulators are available that retain their insulating properties far above the melting points of the nickel-base alloys.

Corrosion. Corrosion of mechanically fastened joints can be reduced considerably using proper design techniques; the section on corrosion discussed the corrosion of nickel-base alloys. Simple procedures of reducing corrosion problems at the design stage are: (1) avoiding electrical contact between dissimilar metals, (2) designing an appropriate joint, (3) choosing a fastener so that a small cathode-to-anode-area ratio is obtained, and (4) avoiding small clearances between the fastener and the joint where concentration cell corrosion might occur.

Sealing. Mechanically fastened joints are rarely leak-tight unless they are sealed. Gaskets are frequently employed for sealing although they reduce the effectiveness of preloaded bolts and decrease the rigidity of a joint. Gasketed joints also tend to have lower fatigue strength than ungasketed joints. Gasket materials have limited usefulness at high-temperature ranges. Silicone rubber, which is one of the best high-temperature sealing materials available, has a temperature range maximum of 500 F, far below the 1600 F service conditions encountered by some nickel-base alloys.

Stress Concentration. Mechanically fastened joints generally require a hole through the joint (e.g., for a bolt or rivet). In thin materials, these holes act as significant stress concentrations that can cause bearing failure of the thin sheet. Because all materials used have some elasticity, any loading of the joint causes the stresses to be unevenly distributed between the fasteners. In brittle materials, the stress concentration at the fastener can cause failure readily.

Galling. Some materials have a pronounced tendency to gall (cold weld) when a concentrated load is placed between two pieces. Galling occurs more readily at higher temperatures. Galling of a fastener can result in a nut seizing on a bolt so tightly during disassembly that the bolt is destroyed before the nut is loosened. Lubricants or coatings have value in decreasing galling. This subject is more thoroughly discussed in a following section.

GENERAL DESIGN CONSIDERATIONS

Standard practices for design of mechanically fastened joints are available in numerous handbooks and codes. Fasteners that can be used for normal and special applications such as those encountered in high-temperature service are described in manufacturers' catalogs. General data on common fasteners are included in the Appendix. A handbook by Laughner and Hargan (Ref. 11) describes the dimensions of a variety of fasteners.

Mechanically fastened joints can be classified as tension or shear joints, and may be either permanent or separable. Permanent joints are usually riveted although threaded fasteners may be used. Threaded fasteners are used for separable joints. In nickel-base alloys threaded fasteners create a special problem in disassembly because of galling and seizing of the threads. This problem is discussed in the section on galling of nickel-base fasteners.

Important considerations in designing the joint are:

(1) The load to be carried

(2) The shear load to be carried by the fastener or the clamped area of the joint

(3) The tension load to be carried by the fastener including preloads on bolts and screws

(4) The type of loading, static or dynamic

(5) The bearing strength of the sheet or plate material in the joint

(6) The tensile strength of the sheet or plate material between holes.

Some basic equations used in arriving at joint and fastener designs are given below (Ref. 11).

Fastener shear load:

$$P_s = S_s A_n \quad ,$$

Fastener load in tension:

$$P_t = S_t A \quad ,$$

Root-diameter area:

$$A_r = 0.7854 \left(D - \frac{1.3}{N}\right)^2 \quad ,$$

Tensile-stress area of threaded section:

$$A_s = 0.7854 \left(D - \frac{0.9743}{N}\right)^2 \quad ,$$

Bearing failure load:

$$P_b = S_b A_b$$

or

$$P_b = S_b t D \quad ,$$

Plate tensile strength:

$$P_u = S_u (W - mD) t \quad ,$$

where

A = root-diameter area of threaded section, sq in.

A_b = area in bearing, sq in.

A_r = effective cross-sectional area, sq in.

A_s = tensile-stress area of a threaded area, sq in.

D = nominal diameter of fastener, in.

m = number of rivets in transverse row

n = number of shear planes

N = number of shear threads per inch

P_b = ultimate bearing strength of joint, lb

P_s = fastener shear load, lb

P_t = fastener load in tension, lb

P_u = tensile failure load, lb

S_b = ultimate bearing strength of plate, psi

S_s = fastener shear stress, psi

S_t = fastener stress in tension, psi

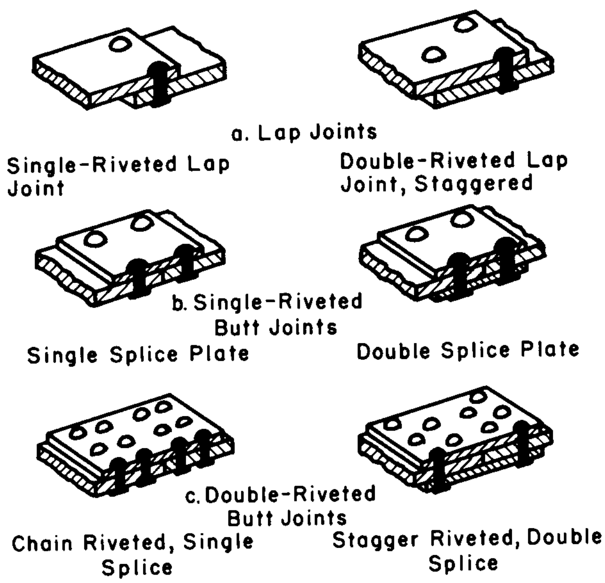
S_u = ultimate tensile strength of plate, psi

W = width of plate, in.

Riveted Joints. Riveted joints are used primarily for joints where the fastener is loaded in shear. The hole spacing and edge distance will be controlled by the loads and the material required to prevent failure in the sheet or plate material. Hole spacing is usually a minimum of 3 times the hole diameter. Minimum edge distances are usually 1-1/2 times the hole diameter. Larger hole spacings and greater edge distances may be required for high-temperature service. Approximate joint efficiencies for riveted joints are given in Table III.

It is important to choose rivets of proper diameter and length for the sheet or plate thicknesses being joined. The rivet hole should be just large enough to permit easy insertion of the rivet. The rivet should fill the hole when upset to prevent movement in the joint. If the joint members can move, the loads on the fasteners are increased over the calculated loads.

TABLE III. APPROXIMATE JOINT EFFICIENCIES FOR RIVETED JOINTS (REF. 11)



Type of Joint	Efficiency, per cent[a]
Butt Joints	
Single	60-70
Double	75-83
Triple	80-89
Lap Joints	
Single	50-60
Double	60-70
Triple	70-80

(a) Ratio of joint strength to strength of thinnest member being joined.

Fatigue failures in riveted joints usually occur in the sheet or plate, not in the rivets. Butt-riveted joints made with multiple rows of rivets have higher fatigue strengths than lap joints or single-row joints.

Bolted Joints. There is a tendency to consider threaded fasteners as tension fasteners regardless of the type of joint used. This is because of the fastener preload used in assembling the joint. In a properly designed and assembled joint a tension fastener will not experience shear loads. The high clamping forces induced by preloading provides more resistance to shearing forces in the joint than the shearing strength of the fastener.

The design considerations for bolted joints are similar to the riveted joints. However, joint strength is affected more by clamping force than by the strength of the fastener. Consequently, it is important to choose the proper preload in order to achieve maximum clamping force. The maximum preload allowable is dependent on the tensile area and the strength of the bolt. Usually threaded fasteners are preloaded to a stress below the yield strength. However, loading plastically does not destroy the usefulness of the fastener. Tensile-stress areas for unified screw threads are given in Table IV.

Clamping force in bolted joints is proportional to the tightening torque. Table V contains suggested tightening-torque values for steel bolts. These may be used as a starting point to choose tightening torques for nickel-base fasteners. About 90 per cent of the applied torque is used to overcome frictional loads rather than tension load the fastener. Consequently, the best way to determine proper tightening-torque values is to experimentally test the joint design with the materials being considered.

DESIGN FOR ELEVATED TEMPERATURES

Bolted joints are used for mechanically fastened joints where fatigue resistance is an important factor. By preloading a bolt to exert force on the joint prior to any external loading on the joint, the fatigue resistance of the joint is increased. Figure 8 illustrates how a preloaded joint composed of rigid materials behaves. As long as the joint load does not exceed the preload tension of the bolt, the bolt tension for a rigid joint does not change as the joint load cycles. Consideration of a joint composed of elastic materials shows that the actual bolting forces are slightly above the bolting force shown in Figure 8. As the joint load increases, the bolting force of elastic

TABLE IV. DATA ON UNIFIED SCREW THREADS FOR CALCULATING STRESSES IN FASTENERS (REF. 11)

		Coarse Series, UNC			Fine Series, UNF		
Size Designation	Nominal Diameter, D, in.	Threads per Inch	Tensile Stress Area, A_s sq in.	Sectional Area at Minor Diameter, A_r sq in.	Threads per Inch	Tensile Stress Area, A_s sq in.	Sectional Area at Minor Diameter, A_r sq in.
0	0.0600	--	--	--	80	0.00180	0.00151
1	0.0730	64	0.00263	0.00218	72	0.00278	0.00237
2	0.0860	56	0.00370	0.00310	64	0.00394	0.00339
3	0.0990	48	0.00487	0.00406	56	0.00523	0.00451
4	0.1120	40	0.00604	0.00496	48	0.00661	0.00566
5	0.1250	40	0.00796	0.00672	44	0.00830	0.00716
6	0.1380	32	0.00909	0.00745	40	0.01015	0.00874
8	0.1640	32	0.0140	0.01196	36	0.01474	0.01285
10	0.1900	24	0.0175	0.01450	32	0.0200	0.0175
12	0.2160	24	0.0242	0.0206	28	0.0258	0.0226
1/4	0.2500	20	0.0318	0.0269	28	0.0364	0.0326
5/16	0.3125	18	0.0524	0.0454	24	0.0580	0.0524
3/8	0.3750	16	0.0775	0.0678	24	0.0878	0.0809
7/16	0.4375	14	0.1063	0.0933	20	0.1187	0.1090
1/2	0.5000	13	0.1419	0.1257	20	0.1599	0.1486
9/16	0.5625	12	0.182	0.162	18	0.203	0.189
5/8	0.6250	11	0.226	0.202	18	0.256	0.240
3/4	0.7500	10	0.334	0.302	16	0.373	0.351
7/8	0.8750	9	0.462	0.419	14	0.509	0.480
1	1.0000	8	0.606	0.551	12	0.663	0.625
1-1/8	1.1250	7	0.763	0.693	12	0.856	0.812
1-1/4	1.2500	7	0.969	0.890	12	1.073	1.024
1-3/8	1.3750	6	1.155	1.054	12	1.315	1.260
1-1/2	1.5000	6	1.405	1.294	12	1.581	1.521
1-3/4	1.7500	5	1.90	1.74	--	--	--
2	2.0000	4-1/2	2.50	2.30	--	--	--
2-1/4	2.2500	4-1/2	3.25	3.02	--	--	--
2-1/2	2.500	4	4.00	3.72	--	--	--
2-3/4	2.750	4	4.93	4.62	--	--	--
3	3.000	4	5.97	5.62	--	--	--
3-1/4	3.250	4	7.10	6.72	--	--	--
3-1/2	3.500	4	8.33	7.92	--	--	--
3-3/4	3.750	4	9.66	9.21	--	--	--
4	4.000	4	11.08	10.61	--	--	--

TABLE V. SUGGESTED TIGHTENING-TORQUE[a] VALUES TO PRODUCE CORRESPONDING BOLT CLAMPING LOADS (REF. 1)

			SAE Grade 2 Bolts					SAE Grade 5 Bolts					SAE Grade 7[c]			SAE Grade 8[d]		
						Tightening Torque					Tightening Torque			Tightening Torque			Tightening Torque	
Size	Bolt Diam, D, in.	Tensile Stress Area, A, sq in.	Tensile Strength, min psi	Proof Load, psi	Clamp[b] Load, P, lb	Dry K=0.20	Lubricated K=0.15	Tensile Strength, min psi	Proof Load, psi	Clamp[b] Load, P, lb	Dry K=0.20	Lubricated K=0.15	Clamp[b] Load, P, lb	Dry K=0.20	Lubricated K=0.15	Clamp[b] Load, P, lb	Dry K=0.20	Lubricated K=0.15
						Lb-In.	Lb-In.				Lb-In.	Lb-In.		Lb-In.	Lb-In.		Lb-In.	Lb-In.
4-40	0.1120	0.00604	69,000	55,000	240	5	4	120,000	85,000	380	8	6	480	11	8	540	12	9
4-48	0.1120	0.00661	69,000	55,000	280	6	5	120,000	85,000	420	9	7	520	12	9	600	13	10
6-32	0.1380	0.00909	69,000	55,000	380	10	8	120,000	85,000	580	16	12	720	20	15	820	23	17
6-40	0.1380	0.01015	69,000	55,000	420	12	9	120,000	85,000	640	18	13	800	22	17	920	25	19
8-32	0.1640	0.01400	69,000	55,000	580	19	14	120,000	85,000	900	30	22	1100	36	27	1260	41	31
8-36	0.1640	0.01474	69,000	55,000	600	20	15	120,000	85,000	940	31	23	1160	38	29	1320	43	32
10-24	0.1900	0.01750	69,000	55,000	720	27	21	120,000	85,000	1120	43	32	1380	52	39	1580	60	45
10-32	0.1900	0.02000	69,000	55,000	820	31	23	120,000	85,000	1285	49	36	1580	60	45	1800	68	51
1/4-20	0.2500	0.0318	69,000	55,000	1320	66	49	120,000	85,000	2020	96	75	2500	120	96	2860	144	108
1/4-28	0.2500	0.0364	69,000	55,000	1500	76	56	120,000	85,000	2320	120	86	2860	144	108	3280	168	120
						Lb-Ft	Lb-Ft				Lb-Ft	Lb-Ft		Lb-Ft	Lb-Ft		Lb-Ft	Lb-Ft
5/16-18	0.3125	0.0524	69,000	55,000	2160	11	8	120,000	85,000	3340	17	13	4120	21	16	4720	25	18
5/16-24	0.3125	0.0580	69,000	55,000	2400	12	9	120,000	85,000	3700	19	14	4560	24	18	5220	25	20
3/8-16	0.3750	0.0775	69,000	55,000	3200	20	15	120,000	85,000	4940	30	23	6100	40	30	7000	45	35
3/8-24	0.3750	0.0878	69,000	55,000	3620	23	17	120,000	85,000	5600	35	25	6900	45	30	7900	50	35
7/16-14	0.4375	0.1063	69,000	55,000	4380	30	24	120,000	85,000	6800	50	35	8400	60	45	9550	70	55
7/16-20	0.4375	0.1187	69,000	55,000	4900	35	25	120,000	85,000	7550	55	40	9350	70	50	10700	80	60
1/2-13	0.5000	0.1419	69,000	55,000	5840	50	35	120,000	85,000	9050	75	55	11200	95	70	12750	110	80
1/2-20	0.5000	0.1599	69,000	55,000	6600	55	40	120,000	85,000	10700	90	65	12600	100	80	14400	120	90
9/16-12	0.5625	0.1820	64,000	52,000	7100	65	50	120,000	85,000	11600	110	80	14350	135	100	16400	150	110
9/16-18	0.5625	0.2030			7900	75	55			12950	120	90	16000	150	110	18250	170	130
5/8-11	0.6250	0.2260	64,000	52,000	8800	90	70	120,000	85,000	14400	150	110	17800	190	140	20350	220	170
5/8-18	0.6250	0.2560	64,000	52,000	10000	100	80	120,000	85,000	16950	180	130	20150	210	160	23000	240	180
3/4-10	0.7500	0.3340	64,000	52,000	13000	160	120	120,000	85,000	21300	260	200	26300	320	240	30100	380	280
3/4-16	0.7500	0.3730	64,000	52,000	14550	180	140	120,000	85,000	23800	300	220	29400	360	280	33600	420	320
7/8-9	0.8750	0.4620	55,000	28,000	9700	140	110	115,000	78,000	27000	400	300	36400	520	400	41600	600	460
7/8-14	0.8750	0.5090	55,000	28,000	10700	155	120	115,000	78,000	29800	440	320	40100	580	440	45800	660	500
1-8	1.0000	0.6060	55,000	28,000	12700	220	160	115,000	78,000	35500	580	440	47700	800	600	54500	900	680
1-12	1.0000	0.6630	55,000	28,000	13900	240	170	115,000	78,000	38800	640	480	52200	860	660	59700	1000	740
1-1/8-7	1.1250	0.7630	55,000	28,000	16000	300	220	105,000	74,000	42300	800	600	60100	1120	840	68700	1280	960
1-1/8-12	1.1250	0.8560	55,000	28,000	18000	340	260	105,000	74,000	47500	880	660	67400	1260	940	77000	1440	1080
1-1/4-7	1.2500	0.9690	55,000	28,000	20350	420	320	105,000	74,000	53800	1120	840	76300	1580	1100	87200	1820	1360
1-1/4-12	1.2500	1.0730	55,000	28,000	22550	460	360	105,000	74,000	59600	1240	920	84500	1760	1320	96600	2000	1500
1-3/8-6	1.3750	1.1550	55,000	28,000	24300	560	420	105,000	74,000	64100	1460	1100	91000	2080	1560	104000	2380	1780
1-3/8-12	1.3750	1.3150	55,000	28,000	27600	640	460	105,000	74,000	73000	1680	1260	104000	2380	1780	118400	2720	2040
1-1/2-6	1.5000	1.4050	55,000	28,000	29800	740	560	105,000	74,000	78000	1940	1460	111000	2780	2080	126500	3160	2360
1-1/2-12	1.5000	1.5800	55,000	28,000	33200	840	620	105,000	74,000	87700	2200	1640	124005	3100	2320	142200	3560	2660

(a) Tightening torque values are calculated from the formula T = KDP, where T = tightening torque, lb-in.; K = torque-friction coefficient; D = nominal bolt diameter, in.; and P = bolt clamping load developed by tightening, lb.

(b) Clamp load is also known as preload or initial load in tension on bolt. Clamp load, lb, is calculated by arbitrarily assuming usable bolt strength is 75 per cent of bolt proof load psi, times tensile-stress area, sq in., of threaded section of each bolt size. Higher or lower values of clamp load can be used depending on the application requirements and the judgment of the designer.

(c) Tensile strength, min psi of all Grade 7 bolts is 133,000 psi. Proof load is 105,000 psi.

(d) Tensile strength, min psi of all Grade 8 bolts is 150,000 psi. Proof load is 120,000 psi.

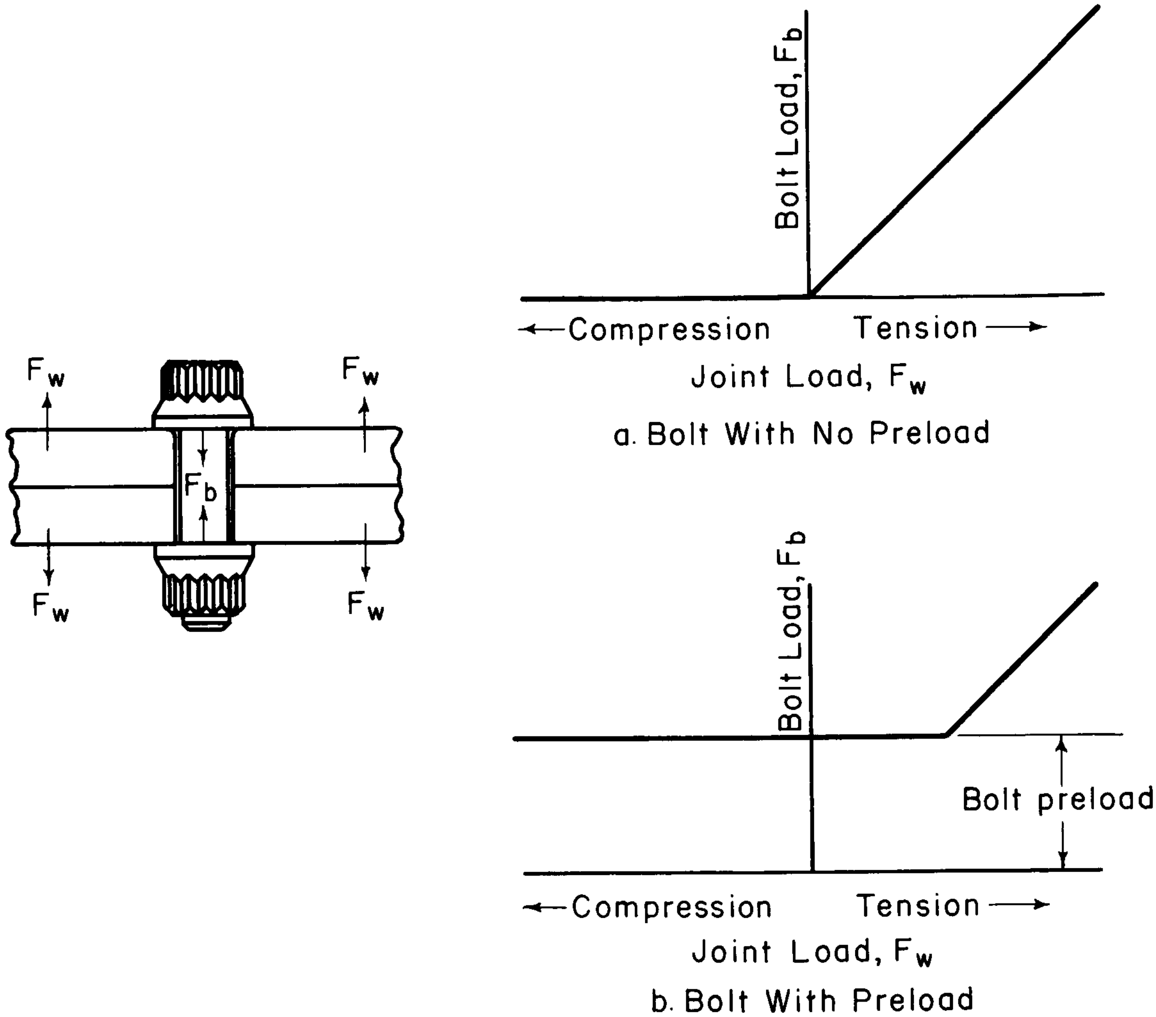


FIGURE 8. RESPONSE OF BOLTED JOINTS TO LOADING

materials increases above the bolting force or rigid materials. Thus, in an elastic joint, the bolting force does cycle with the joint load to a small degree even if the joint load is less than the preload. Several physical properties of the metals composing a joint that will be used at high temperature should be considered during joint design. These are the coefficient of thermal expansion, the modulus of elasticity, and the relaxation characteristics of the joint.

Coefficient of Thermal Expansion. For most materials, a part will increase in size as the temperature increases. If the bolt material is different from the joint material, then the material with the higher coefficient of thermal expansion will undergo the greater increase in size. If the bolt has the larger coefficient, the bolt preload will decrease as the temperature increases. Consequently, the allowable working load decreases. If the pieces being joined had the larger coefficient, the bolt preload would increase. Permanent deformation and fatigue due to thermal cycling could result. The thermal coefficients of nickel-base alloys and other structural materials are compared in Figure 6.

Modulus of Elasticity. As temperature increases, the amount of stress necessary to produce a given elastic deformation decreases. This decrease in the modulus of elasticity causes a structure to be less rigid and also decreases the bolt preload. This, in turn, decreases the allowable working load. Joint design must compensate for this loss in load capacity.

Relaxation Characteristics. The phenomenon of permanent deformation of a material over a time period (creep) is well known. Relaxation is a similar process that occurs in mechanically fastened joints. However, the load during relaxation steadily decreases as the fastener length increases. This causes a decrease of the preload. At elevated temperatures, the relaxation properties of materials become very important for preloaded, mechanically fastened joints. After accounting for the thermal expansion and the decrease in the modulus of elasticity, a designer must select materials that will have the desired strength properties for the service life of the joint.

GALLING OF NICKEL-BASE FASTENERS

Aerospace equipment fabricators have indicated that high-nickel alloys have a tendency to gall during installation (Ref. 6). The galling tendencies of Waspaloy, M-252, and René 41 nuts have been studied (Ref. 12). It was concluded that a proprietary molybdenum disulfide lubricant baked on the bolt and nut gave satisfactory and reproducible results with minimum galling. Waspaloy was recommended over M-252 material for self-locking nuts. After 1-hour exposure to 1600 F, the M-252 nut was not reusable after removal. Waspaloy nuts have been tested by being assembled, exposed to 1600 F for 1 hour, removed, reassembled, and then recycled 14 additional times. These nuts were then exposed to 2000 F for 1/2 hour, removed, reassembled, and recycled one more time. After these tests, the nuts were still reusable. However, it was recommended (Ref. 12) that for the fastener materials studied, the nut should be replaced after each exposure to temperatures between 1600 and 2000 F. Tables established by the military recommend installation torques for cadmium-plated steel bolts which arbitrarily establish the maximum installation torque as the nut torque that produces a bolt stress of 90 per cent of the rated bolt stress. Normal installation was established at 45 to 60 per cent of this value. It has been concluded (Ref. 12) that the installation torques established for cadmium-plated steel bolts are satisfactory for equivalent-strength nickel-base fasteners if

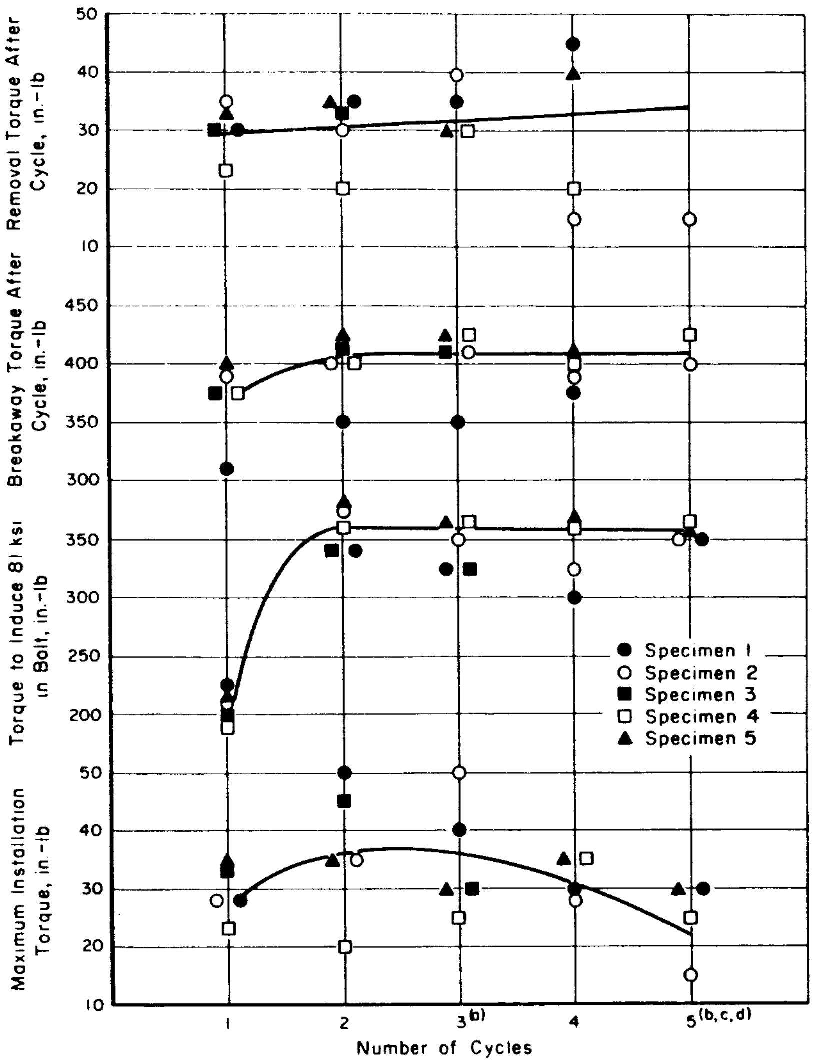
(1) The nut or bolt is exposed for 1400 F at least 2 hours to form a minimum oxide coating

(2) A proprietary molybdenum disulfide lubricant is applied to the nut and bolt in liquid form or baked on the nut.

Glackin and Gowen (Ref. 6) determined the nut reuse and galling tendencies of No. 10 and 1/4-inch-diameter unlubricated, silver-plated Waspaloy nuts and bolts after cycling to -423 F, 1400 F, and room temperature for 5 minutes. The test procedures employed closely paralleled those of AMS 7250. Figure 9 shows the results of tests after cycling to 1400 F. The figure shows the greatest change in the fastener-installation characteristics occurred between the first and second cycle. After the second cycle, the bolts showed no significant trends except for a decreasing maximum installation torque and a slightly increasing removal torque. Some tests at 1600 F showed nut galling and seizure to be so severe for silver-plated Waspaloy fasteners that the fasteners should not be used at 1600 F or should be used only in very limited applications.

COATING OF FASTENERS

When galling of a threaded fastener causes an undesirable increase in tightening torque or causes difficulty in removing the



(a) Specimen 3 - galled during removal.
(b) Specimen 1 - bolt broke during breakaway.
(c) Specimen 4 - galled during removal.
(d) Specimen 5 - bolt broke during breakaway.

FIGURE 9. GALLING OF UNLUBRICATED WASPALOY BOLTS AND NUTS AT 1400 F (REF. 6)

Material: 1/4-28 Waspaloy (150 ksi) bolt and nut (silver plated)

Cycle: heat to 1400 F, hold 5 minutes, test at room temperature.

fastener, the fastener is coated. The factors that cause bolt seizure are (Ref. 13):

(1) Environment. Exposure to high temperatures, liquids, fumes, or to a vacuum increases galling

(2) Material. Choice of alloys that are not corrosion resistant in the service application and that have inadequate strength or hardness increases galling problems

(3) Fastener. Out-of-tolerance thread dimensions, the quality of the surface finish, and contamination of the fastener affect the tendency to galling. In addition, the control of the driving torque is a significant factor in galling.

Environment. The exposure of fasteners to high temperatures greatly increases their susceptibility to corrosion by the service environment. Even minute traces of a contaminant on the fastener can cause significant corrosion. The corrosion products of wet or dry corrosion can cause seizure of the bolt (Ref. 13). Also, corrosion can reduce the surface finish quality on the threads and cause an increased tendency to gall. Operation in a vacuum can cause galling to become pronounced, particularly in conjunction with high temperatures. Many lubricants and protective surface films evaporate in a vacuum leaving the threaded parts in intimate, metal-to-metal contact. Such a situation is favorable to diffusion bonding of the fastener to the nut or tapped hole, particularly at elevated temperatures with cyclical loading.

Material. The relative hardness of the metals in contact influences galling tendencies (Ref. 13). The specification of nuts that are softer than the bolt usually promotes galling, instead of retarding it. Softer materials are more likely to deform when tightened. Thus, a larger amount of metal-to-metal contact occurs between the threads of the nut and bolt.

Use of fastener materials with two or more metallurgical phases can limit galling. The different hardness of the adjacent phases limits the amount of metal-to-metal contact thereby eliminating the amount of cold welding. The harder and higher tensile strength materials are much less prone to galling than softer alloys. Coating of a soft material with a hard alloy can reduce galling.

Fastener. Excessive interference of the bolt threads with the nut or tapped hole due to poor machining tolerances or failure to allow for coatings increases the amount of metal-to-metal contact and the galling tendency of the fastener. This increases the required driving torque and the possibility of permanent deformation of the fastener before the fastener is torqued to a specified preload. Roughly finished threads can strip off protective surfaces during tightening and can also form points of metal-to-metal contact with the other threaded component.

Surface Coatings. Surface coatings are used either to increase the corrosion resistance of the fastener or to provide a lubricant at the threaded surfaces. Coating materials should be chosen with full knowledge of the possible metallurgical reactions that might occur. The simplest example of this would be the use of cadmium-plated bolts in a high-temperature service application. Cadmium melts at about 610 F and would braze the nut to the bolt if heated above this temperature. This makes removal very difficult. Another example is the use of silver-plated titanium bolts. Titanium, which is extremely sensitive to galling due to its high chemical reactivity, does not gall readily when the threads are silver plated. However, the stress-rupture properties of titanium are decreased significantly when exposed to sodium chloride in the presence of silver.

The following coatings are listed in the approximate order of their usable temperature range. The first coatings listed have the lowest maximum service temperature.

Cadmium. Cadmium is the most widely used fastener surface coating. Cadmium can be used either as an anodic protection coating for corrosion resistance or as a thin film lubricant at temperatures up to 450 F. The primary use for cadmium plating has been with steel and stainless steel alloys.

Tin-Nickel. A 65 per cent tin-35 per cent nickel alloy is suitable for coating bolts for use at temperatures as high as 650 F (Ref. 13). It is a hard coating with good lubricant properties and can be electroplated on many steel, copper, and stainless steel alloys.

Nickel Cadmium. A diffused nickel-cadmium alloy has been used to increase the corrosion resistance of steel alloys (Ref. 6). The coating is used up to 900 F.

Molybdenum Disulfide. This material is used with a variety of carriers to act as a lubricant at temperatures up to 900 F.

Black (Ref. 14) states that MoS_2 readily changes above 900 F to MoO_3, which has no lubricating action. However, Elfalen (Ref. 12) has reported successful use of a proprietary MoS_2 lubricant for a total of 15 hours at 1600 F and 1 hour at 2000 F. Molybdenum disulfide is the lubricant most widely used by aerospace fabricators (Ref. 6). However, this lubricant should not be used in vacuum service or in proximity to liquid oxygen (Ref. 6).

Aluminum. Although little experience has been obtained with aluminum-coated steel bolts, it appears that the coating could be used on low-alloy bolts at temperatures up to 1100 F (Ref. 13). At these temperatures, low-alloy steels oxidize readily if they are not protected. Aluminum plating is also used for thermal control (Ref. 6).

Graphite. Graphite is a low-cost lubricating material used with a variety of carriers at temperatures to 1100 F and, in some special cases, up to 1500 F (Ref. 13). Although graphite is corrosion resistant at high temperatures, it is more noble than most fastener materials and can cause rapid corrosion of the fastener in the presence of an electrolyte, particularly at high temperatures.

Copper. Copper particles are widely used dispersed in a carrier. It can also be electroplated to steel to be used in high-temperature applications.

Silver. Silver has been widely used with austenitic stainless steel fasteners in high-temperature applications. Generally, this coating can be used up to 1100 F.

Chromium. Chromium provides a hard, wear-resistant, corrosion-resistant coating when it is electroplated. However, the plating characteristics of chromium make a uniform coating difficult to obtain. The high corrosion resistance of chromium can also cause difficulties when the fastener is placed in an electrolyte. At any point at which the bolt material is exposed to the electrolyte, corrosion will readily occur because of a large and unfavorable cathode-to-anode-area ratio.

Vermiculite. Black (Ref. 14) reports that a micaceous material, vermiculite, has lubricating properties at temperatures above the maximum for silver or graphite.

Proprietary lubricants are available for specialized applications from commercial sources. Many are combinations of the materials previously discussed.

NICKEL-BASE-ALLOY FASTENER STANDARDS

The development of a large number of high-strength alloys has been so recent that many nickel-base-alloy fasteners can be manufactured only to specifications developed by the manufacturer or customer. The existing specifications for nickel-base fasteners are listed in Table VI.

TABLE VI. SPECIFICATIONS FOR NICKEL-BASE FASTENERS

Rivets, nickel, 15.5Cr, 8.0Fe	AMS 7232E
Rivets, solid, Monel	AMS 7233A
Rivets, blind, Monel	AMS 7234B
Rivet, universal head, Monel	NAS 508
Bolts and screws, nickel base, upset headed, heat treated, roll threaded	AMS 7469

SELECTION OF MECHANICAL FASTENERS

The type of fastener used in a specific application depends upon the considerations taken during design. Besides the factors of reusability, strength, corrosion resistance, etc., the fastener actually is selected because of the cost, availability, and equipment required to use a specific fastener. Previous shop experience is also an important factor. Most nickel-base alloys can be manufactured in any design if the customer is willing to pay the price and wait for production of the item. Fastener manufacturers should be contacted for specific information and for details of new, proprietary features. The following sections discuss considerations that should be made when selecting a fastener.

The use of a fastener material similar to the materials being joined is often preferable because the design problems of dissimilar metal corrosion, differential thermal expansion, and differences in the change of mechanical properties with temperature are all reduced when the fastener and joint material are similar. However, nickel-base alloys are not always available in the desired fastener configuration. Because of difficulty in forming and machining, nickel-base fasteners are usually available on a limited, special-order basis from fastener manufacturers. High-strength steels and stainless steels are frequently used to fasten nickel-base alloys. Glackin and Gowen (Ref. 6) reviewed the use of nickel-base fasteners by aerospace fabricators and found them being used in structures near engines or on re-entry vehicles with exposure to temperatures as high as 1800 F. Stress-rupture and stress-relaxation properties were listed as the governing factors in nickel-base-alloy selection. Waspaloy and Monel were two alloys that had shown exceptionally good cryogenic performance. Hastelloy and Monel fasteners have been used extensively due to their compatibility with corrosion-resistant Monel and Hastelloy structures. The following sections describe briefly fastener information for a number of nickel-base alloys.

Monel. Monel is widely used in the form of cold-deformable rivets. The alloy has excellent corrosion resistance in a variety of environments and has been used successfully from cryogenic temperatures (-400 F) to 1600 F. A ductile to brittle transition has not been observed for the alloy even at cryogenic temperatures (Ref. 6).

René 41. René 41 has been widely used because it was one of the first nickel-base superalloys available. René 41 is apparently notch sensitive at cryogenic temperatures (Ref. 6). René 41 is used primarily at elevated temperatures.

René 62. René 62 is a new alloy that has a maximum applicable temperature rating of 1500 F. The alloy can provide high strength after heat treatment. Very little experience has been obtained with this alloy.

Waspaloy. Waspaloy fasteners appear to be very promising for use at cryogenic temperatures. Tests on Waspaloy fasteners (Ref. 6) from -423 to 1400 F showed the material to have consistent notch ductility. Figures 10 through 12 show mechanical properties of Waspaloy fasteners from -423 to 1400 F.

Udimet 630. Udimet 630 has high tensile and yield strengths up to 1300 F. In recent tests, fasteners fabricated from Udimet 630 have shown good ductility at cryogenic temperatures. Figures 10 through 12 illustrate the variation of the fastener mechanical properties with temperature.

AF 1753. AF 1753 was developed by the United States Air Force for high-temperature applications. Recent tests show that

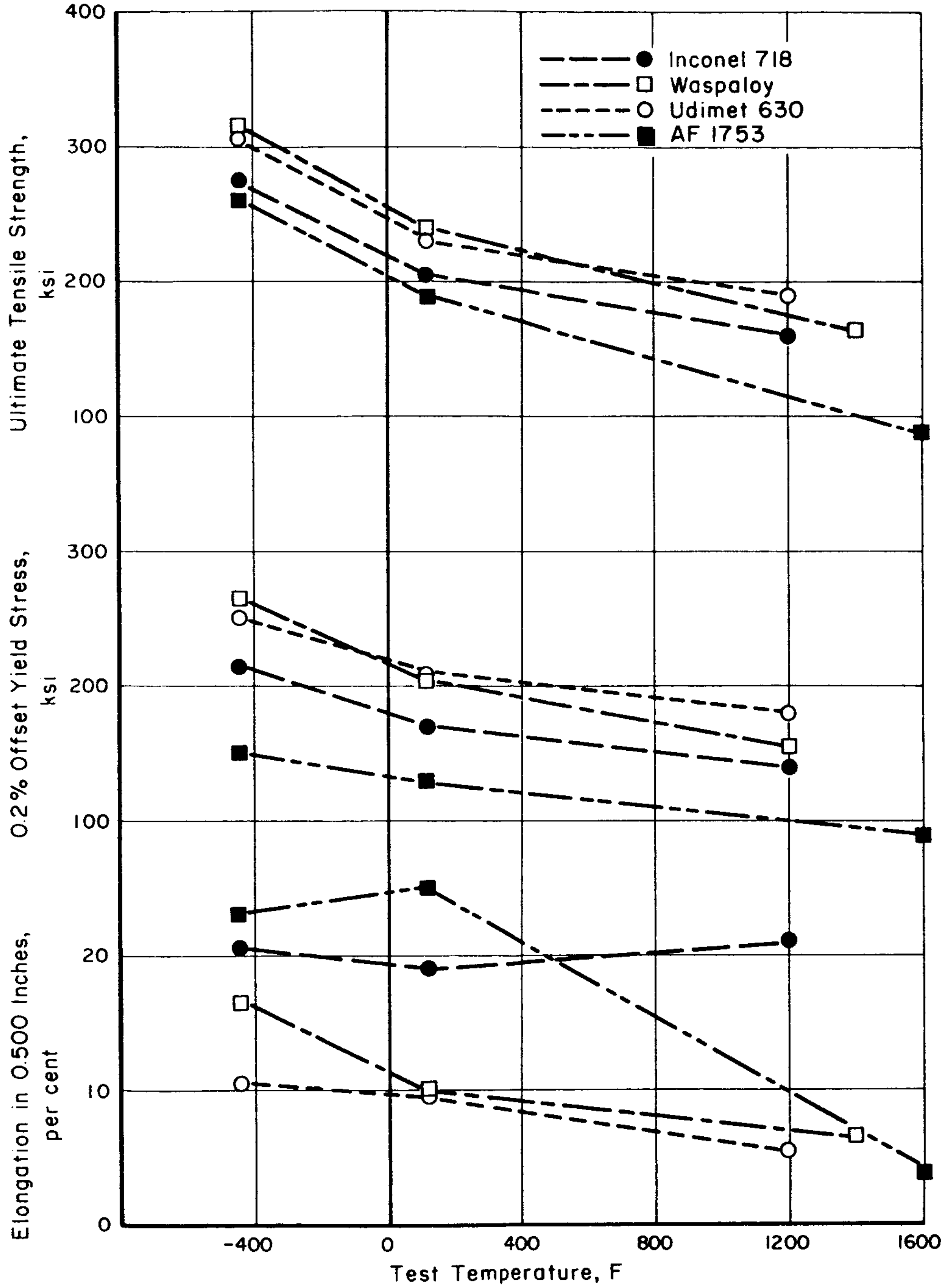


FIGURE 10. PROPERTIES OF 0.113-INCH-DIAMETER TENSION BOLTS (REFS. 6, 15)

Each plotted point is the average of three tests.

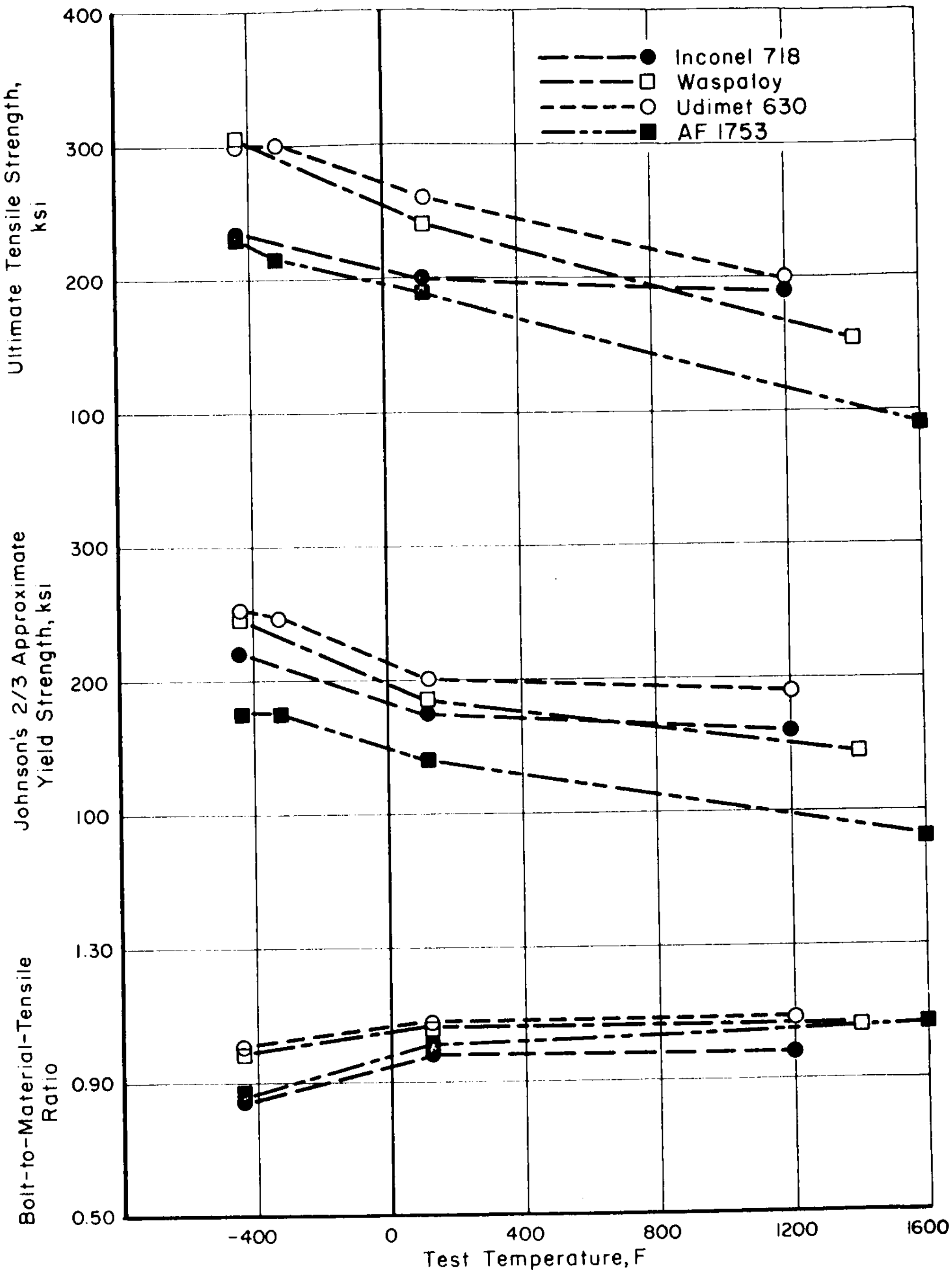


FIGURE 11. TENSION PROPERTIES OF 1/4-28 BOLTS (REFS. 6,15)

Each plotted point is the average of three tests.

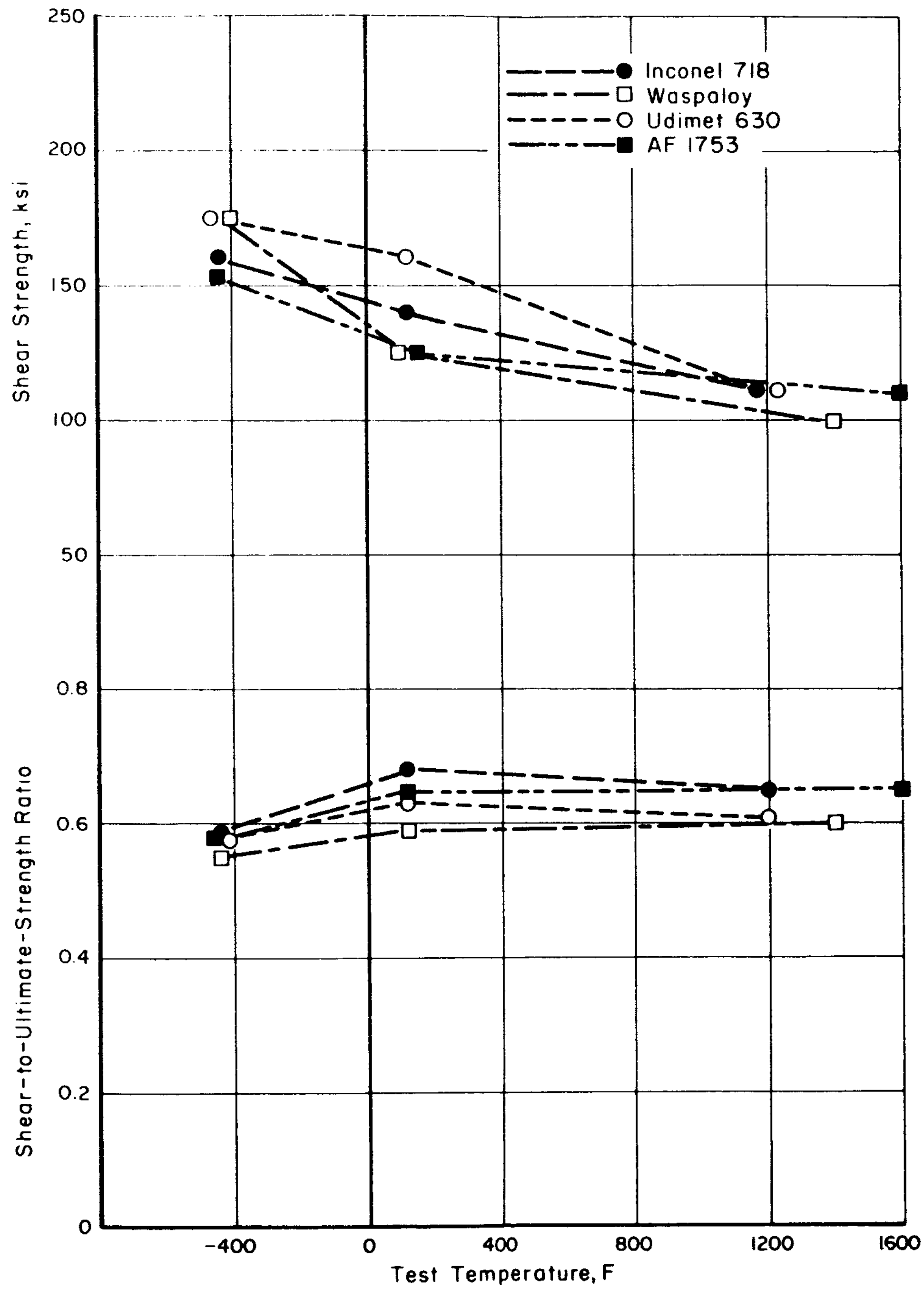


FIGURE 12. SHEAR PROPERTIES OF 1/4-28 BOLTS (REFS. 6,15)

Each plotted joint is the average of three tests.

this material has satisfactory mechanical properties from -423 to 1600 F as shown in Figures 10 through 12.

Inconel 718. Inconel 718 has been demonstrated to have good mechanical properties from -423 F to 1200 F as shown in Figures 10 through 12.

Udimet 700. Udimet 700 is a new alloy with relatively little data available on its properties. It is believed that the material may have good cryogenic properties (Ref. 6).

Hastelloy X. Hastelloy X has been demonstrated to be a useful fastener material that has good high-temperature strength at temperatures up to 1200 F as shown in Figures 13 and 14.

M-252. Rivets and bolts have been fabricated from M-252 alloys and tested extensively (Ref. 16). Figures 15 through 17 show that fasteners fabricated from this material have high-strength properties even in the 1200 to 1400 F range.

JOINT PROCESSING

FORMING OF JOINTS

The forming operations of joggling and dimpling are the two processes most often used when joints are mechanically fastened. Strohecker, et al., (Ref. 17) give more detailed information on these two and other processes.

Joggling. Joggles are commonly used to join sheet together to obtain a flat surface on one side of the joint. A large number of joggling methods and types of joggling equipment are available. Hydraulic presses are frequently used for elevated-temperature joggling because the control of pressure and dwell time is simple (Ref. 17). Nickel-base alloys frequently have been joggled at room temperature. Nickel-chromium-molybdenum tool steels give satisfactory service for tools used at room temperature (Ref. 17). For higher temperatures, high-strength, heat-resistant alloys, or ceramic materials are usually required for tools.

High-pressure drawing lubricants containing inert filler and having a high film strength are satisfactory for joggling nickel-base alloys (Ref. 17). Care must be taken to remove the lubricant prior

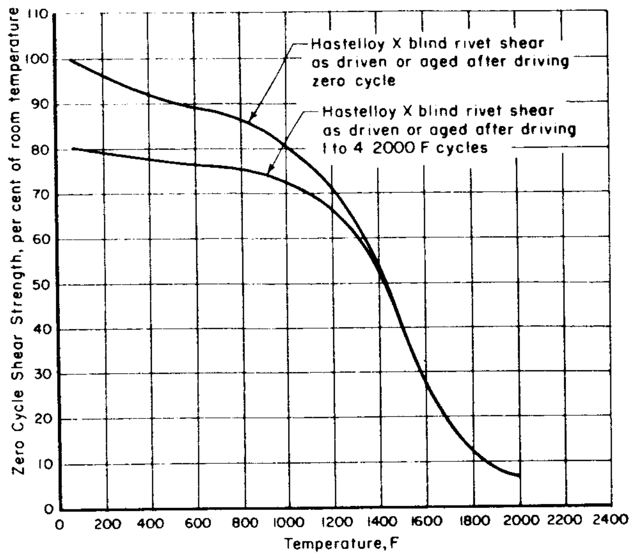


FIGURE 13. HIGH-TEMPERATURE SHEAR STRENGTH OF HASTELLOY X BLIND RIVETS (REF. 16)

Aged rivets were aged 16 hours at 1400 F after installation; soak time: 20 minutes at temperature; load rate: 0.02 in./min.

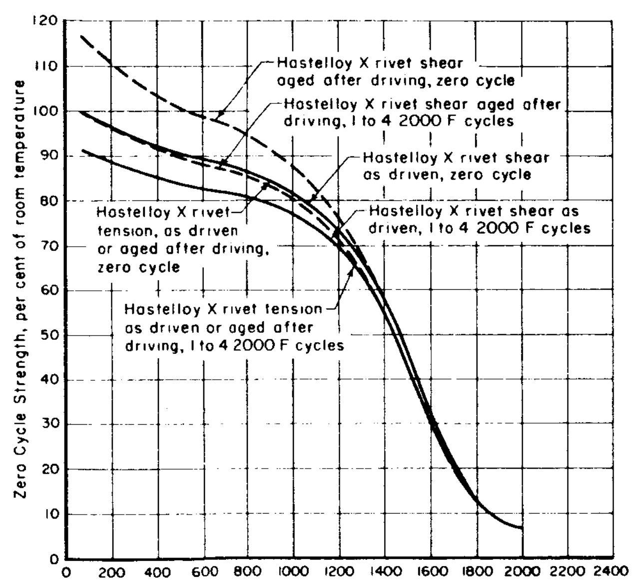


FIGURE 14. HIGH-TEMPERATURE TENSILE AND SHEAR STRENGTHS FOR HASTELLOY X RIVETS (REF. 16)

Aged rivets were aged 1 hour at 1400 F after installation; soak time: 20 minutes at temperature; tension load rate: 100 ksi/min.; shear load rate: 0.02 in./min.

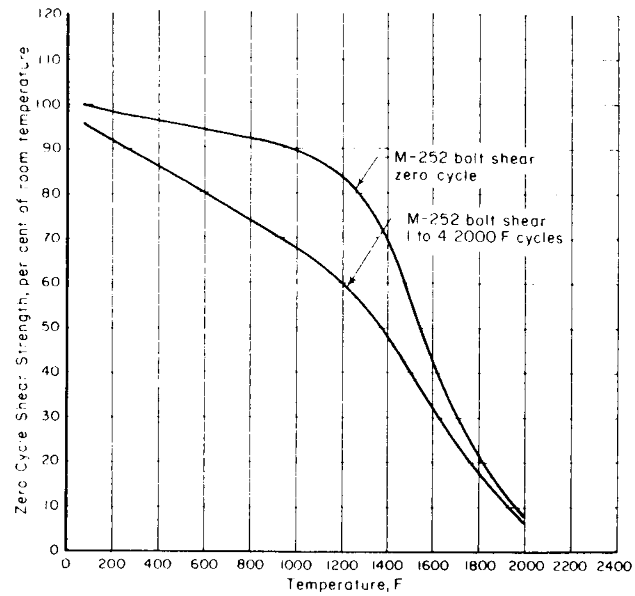


FIGURE 15. HIGH-TEMPERATURE SHEAR STRENGTH OF M-252 BOLTS (REF. 16)

Soak time: 20 minutes at temperature; load rate: 100 ksi/min.

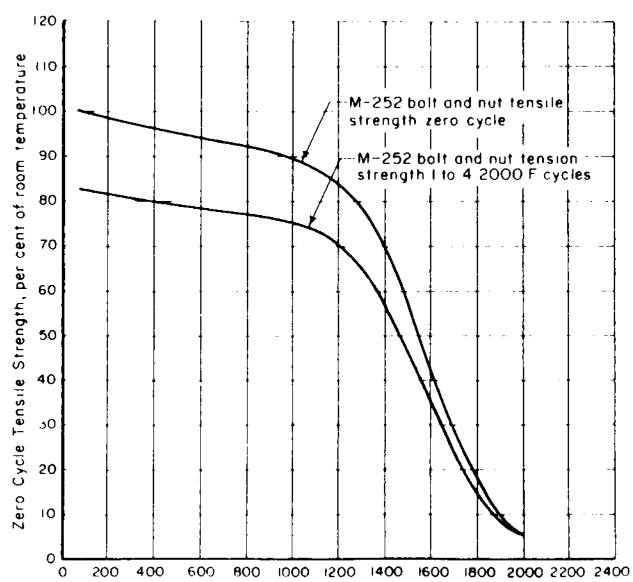


FIGURE 16. HIGH-TEMPERATURE TENSILE STRENGTH OF M-252 BOLTS AND NUTS (REF. 16)

Soak time: 20 minutes at temperature; load rate: 100 ksi/min.

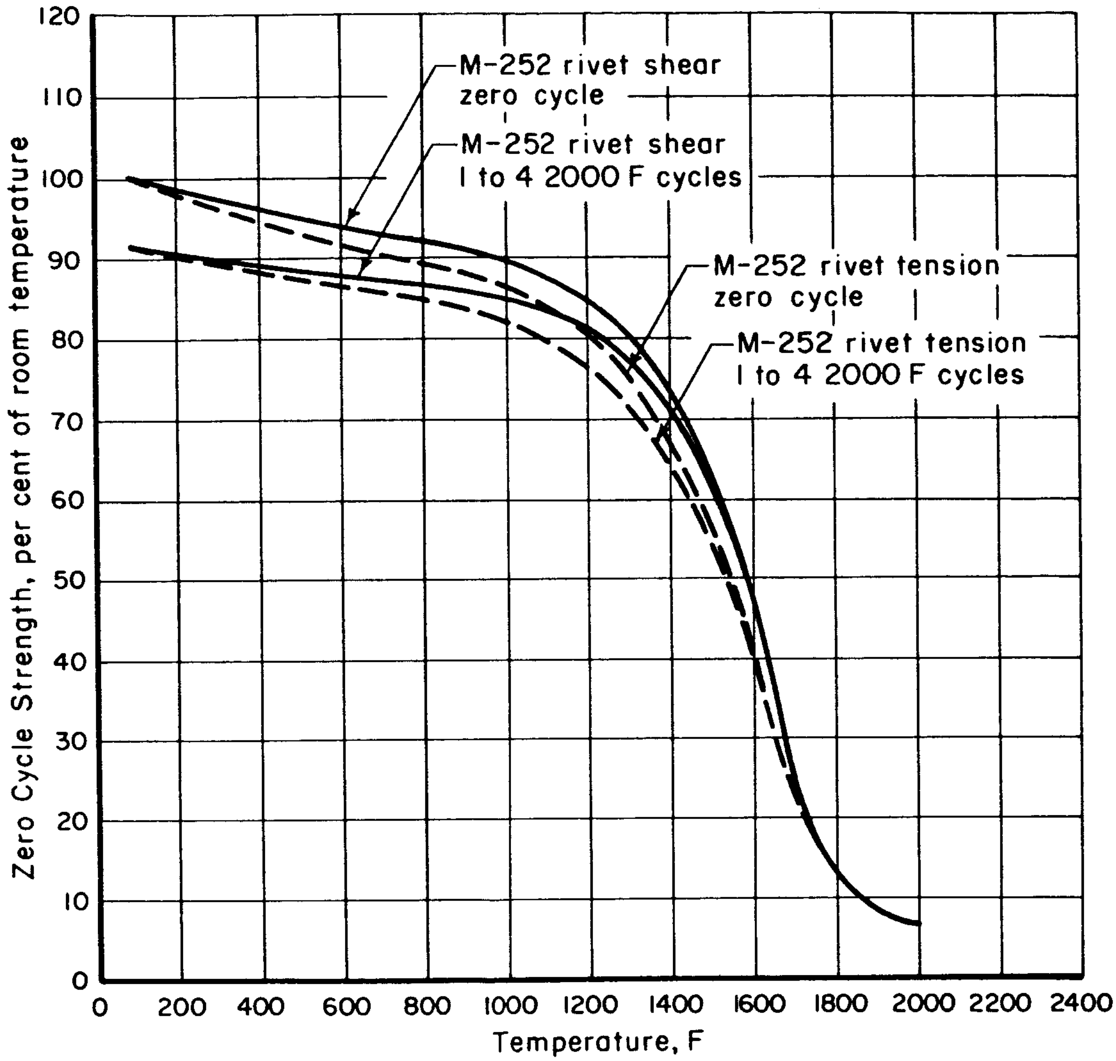


FIGURE 17. HIGH-TEMPERATURE SHEAR AND TENSILE STRENGTHS OF M-252 RIVETS (REF. 16)

Aged rivets were aged 1 hour at 1400 F after installation; Soak time: 20 minutes at temperature; tension load rate: 100 ksi/min; shear load rate: 0.02 in./min.

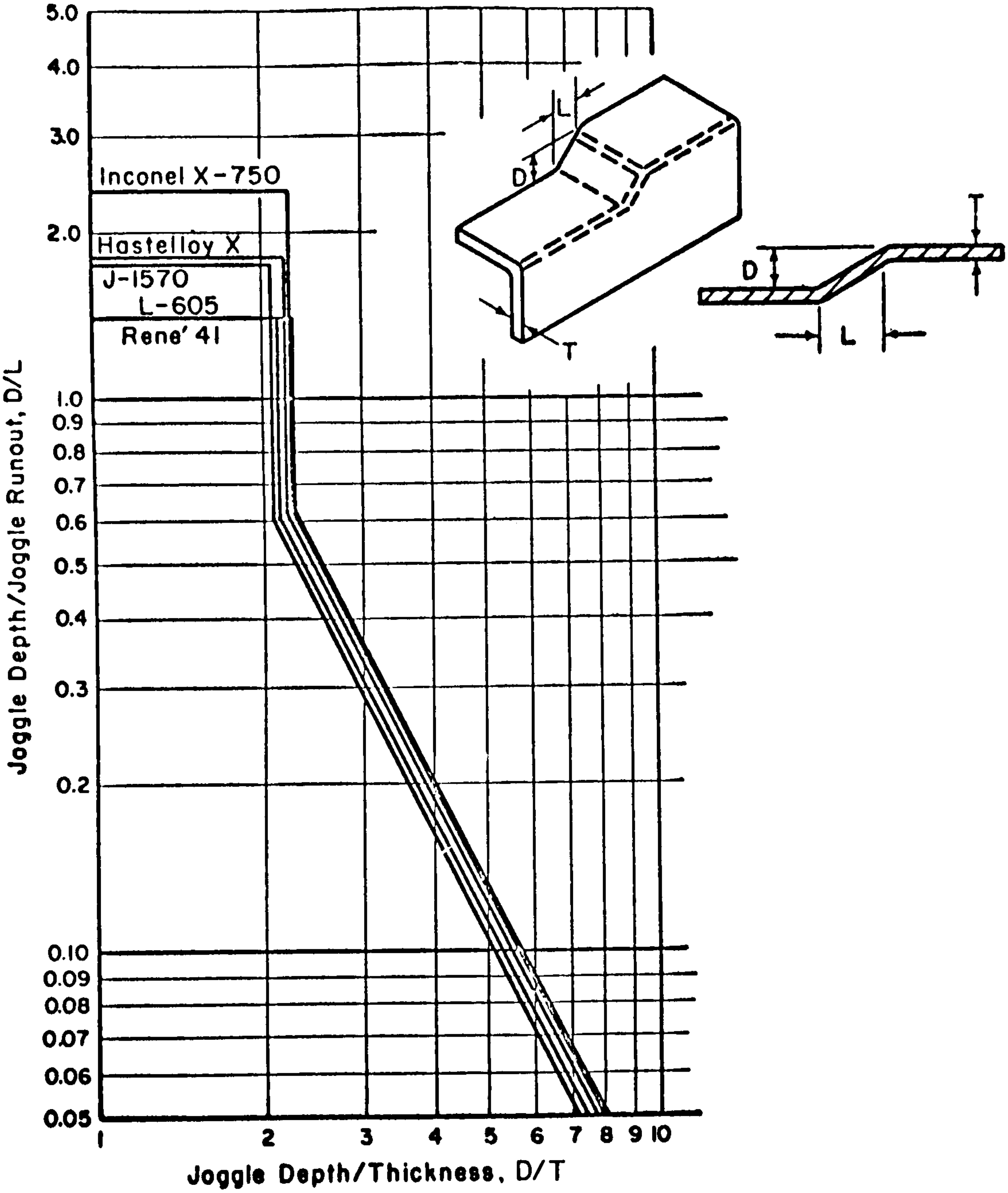


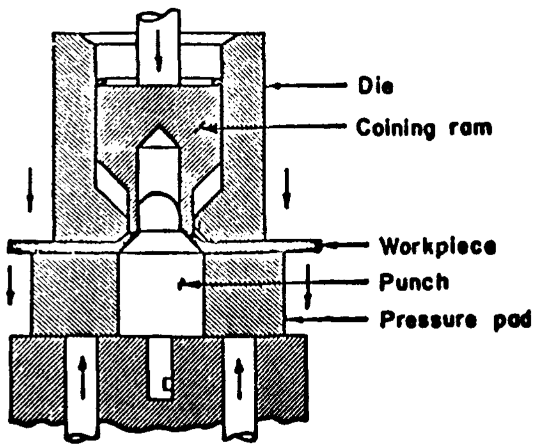
FIGURE 18. LIMITING DESIGN PARAMETERS FOR JOGGLING NICKEL-BASE ALLOYS (REF. 18)

to any thermal treatment, particularly if sulfurized oils or greases are used. Figure 18 contains suggested joggling parameters for nickel-base alloys.

Springback in joggled sheet formed at room temperature varies from 5 to 10 per cent. Generally, parts are overbent to allow for the springback. After thorough cleaning to remove forming lubricants, joggled and formed parts are solution heat treated and aged. Distortion during heat treatment can be reduced by clamping in fixtures. Alloys such as René 41 shrink 0.0005 inch per inch during aging (Ref. 10). This shrinkage is significant when large parts are fabricated.

Dimpling. Dimpling is frequently used in fabricating thin-sheet materials with all fasteners flush with one side of the joint. Dimpling is primarily used for sheet that is too thin to be countersunk by machining. The dimple is a conically shaped indentation formed around the hole for a flat-headed fastener. Dimpling should always be done on sheet that has been thermally treated to the final service condition. Thermal treatment after dimpling can result in distortion of the sheet and subsequent misalignment of drilled holes.

The deformation allowable in a dimpled area is dependent upon the material ductility. Material that does not have sufficient ductility for a given amount of deformation during dimpling will crack either radially from the hole (common in thick stock) or circumferentially around the dimple (common in thin stock) (Ref. 17). Dimpling can be accomplished at room temperature for many nickel-base alloys that have good ductility. Some alloys must be dimpled at elevated temperatures, however. Ram-coin dimpling is most commonly used to produce dimples (see Figure 19). Figure 20 illustrates the operations for



IGURE 19. CROSS SECTION OF RAM-COIN-DIMPLING TOOLING (REF. 19)

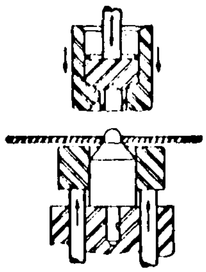
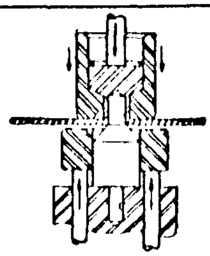
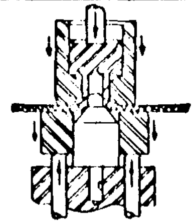
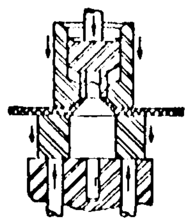
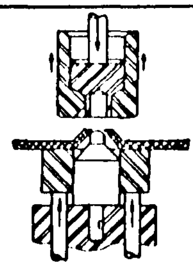
Position 1		**a. Approach** Sheet is positioned, with punch pilot in pilot hole and die assembly is coming down to contact position; loading force on coining ram is at preselected value
Position 2		**b. Preform** Die assembly has just contacted work, and timed heating stage is beginning; controlled preforming pressure is increasing to partially form dimple and to further accelerate heat transfer
Position 3		**c. Coining** Timed "Preform" stage has ended, and final coining stage begun; downward movement of die assembly is creating firm gripping action between die and pad faces in area around dimple, preventing outward flow of material as dimple is coined; coining ram controls hole stretch and balances internal strains, eliminating radial and internal shear cracks
Position 4		**d. End of Stroke** Dimple is now fully formed; the confining action of pad face, die face, and coining ram has forced material into exact conformation with tool geometry
Position 5		**e. Retraction** As die assembly retracts to starting position, load on pressure pad raises pressure pad to starting position and strips dimple from punch cone **f. Result** Minimum sheet stretch, minimum hole stretch, maximum definition, improved nesting

FIGURE 20. SEQUENCE OF OPERATIONS IN TRIPLE-ACTION RAM-COIN DIMPLING AT ELEVATED TEMPERATURES

Courtesy of Convair, General Dynamics Corporation, San Diego, California.

triple-action ram-coin dimpling. If dimpling is done hot, conduction heating of ram-coin tooling can be used up to 1000 F. Resistance heating of the tooling is used for higher temperatures.

The drilled pilot hole must be smooth, round, cylindrical, and free of cracks, nicks, or burrs. Chatter marks left during deburring should be avoided. If these precautions are not observed, these defects can act as stress-concentration points during dimpling.

Three temperature ranges exist for dimpling nickel-base alloys (Ref. 17):

(1) Room temperature

(2) Below the precipitation-hardening temperature

(3) Near the solution-treating temperature.

Inconel X-750 has been dimpled at room temperature (Ref. 20). For thicknesses greater than 0.020 inch, better results have been obtained at 600 F (Ref. 21).

Properly dimpled holes often retain 85 to 95 per cent of the sheet cross section and material strength around a rivet hole (Ref. 22). Some investigations have been made of the properties of dimpled joints in Inconel X-750. The fatigue properties of bolted and riveted joints are shown in Figures 21 and 22. The dimpled joints in 0.020 sheet had ultimate loads as high as 1,160 pounds for each No. 10 screw and 1,610 pounds for each 1/4-inch rivet (Ref. 20). The yield load was 1,090 pounds for each No. 10 screw and 1,450 pounds for each 1/4-inch rivet.

MACHINING OF JOINTS

The machining operations of drilling, reaming, and tapping are generally performed just prior to assembly. Subsequent forming or heat treatment can result in serious misalignment of the pieces. An exception is the requirement that the holes must be drilled in the sheet prior to dimpling. Further details on the drilling, reaming, and tapping of nickel-base alloys and on other processes are reported by Olofson, et al. (Ref. 5).

Nickel-base alloys are regarded as difficult-to-machine materials primarily because of their tendency to work harden when machined in the annealed or solution-heat-treated condition (Ref. 5). This type of behavior is similar to that of stainless steels. The selection of tool

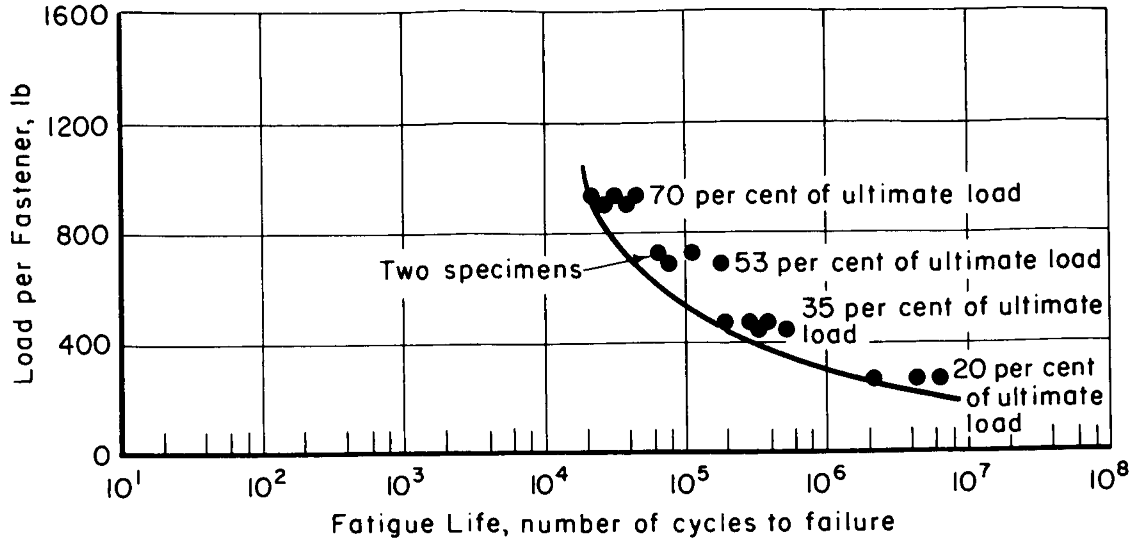


FIGURE 21. S-N FATIGUE CURVES FOR 0.020-INCH-THICK INCONEL X-750 SHEET FASTENED WITH NO. 10 STAINLESS STEEL SCREWS (REF. 20)

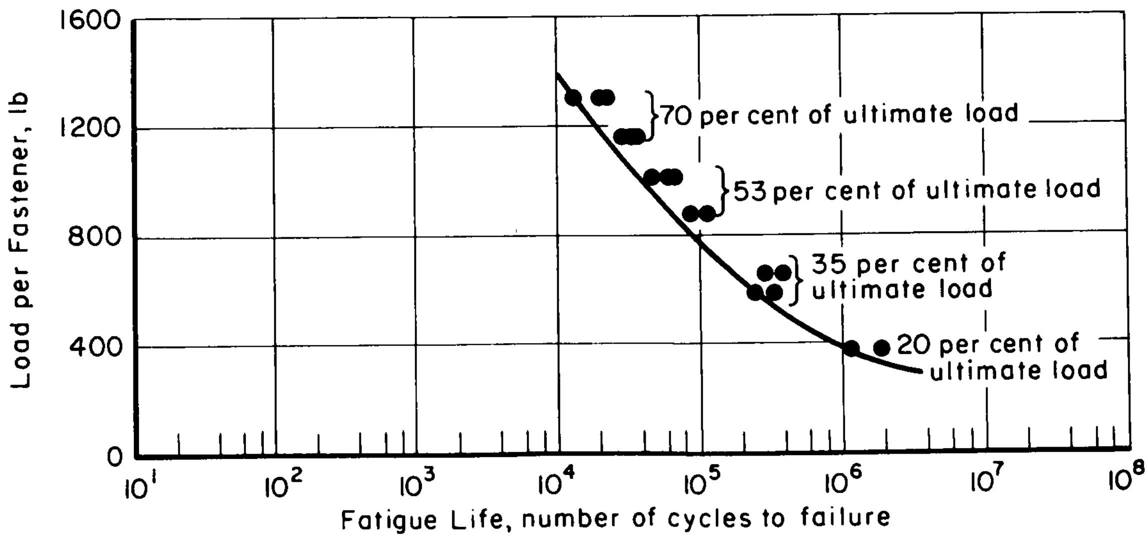


FIGURE 22. S-N FATIGUE CURVES FOR 0.020-INCH-THICK INCONEL X-750 SHEET FASTENED WITH 1/4-INCH STAINLESS STEEL RIVETS (REF. 20)

and cutter designs, machining setups, cutting parameters, and lubricants significantly affect the ease of machining. Investigators have noted that the margin between success and failure in machining nickel-base alloys is a narrow one (Ref. 23). Performance is dependent upon the entire machining environment, including the operator. The data available on machining nickel-base alloys do not indicate special procedures for machining the different classes of nickel-base alloys other than slight modifications of the tool geometry and possible changes in cutting speeds.

Drilling. The thrust and torque forces required during the drilling of nickel-base alloys are considerably greater than when machining conventional alloys. In addition, the center web of the drill, which does not cut, work hardens the material ahead of the cutting edges of the drill. The work-hardened material requires higher cutting forces and causes early drill failure. The use of thin-webbed drills and positive drilling feeds prolongs drill life (Ref. 24). Improper drilling can result in out-of-round, smeared, wandering, out-of-tolerance holes, which greatly impair precise reaming and tapping.

Design and manufacturing engineers can avoid high scrap losses by specifying five items (Refs. 24-28):

(1) Shallow holes

(2) Short, sharp drills with large flutes and special points

(3) Supply of sufficient and proper lubricant to the cutting edges

(4) Use of low and positive drill speeds

(5) Support of the exit side of the through hole to prevent burr formation.

The drilling machine must be rigidly constructed to withstand the high forces required to machine nickel-base alloys. Spindle overhang, bearing play, and drive backlash should be minimized (Ref. 26). Portable high-speed drills with spindle speeds ranging between 230 and 550 rpm at 90-psi air pressure are good units to use at assembly location.

Drills. High-speed tool steels are widely used for drilling nickel-base alloys. Carbide drills are generally limited to deep holes because of high cost, high breakage rates, and limited tolerances to wear. Good success has been achieved with molybdenum-tungsten high-speed drills (Ref. 26). Cobalt high-speed drills have generally performed better than standard high-speed tool steels (Refs. 25, 26).

The drill strength and rigidity must be high to machine nickel-base alloys successfully (Ref. 29). Thus, the specification of short holes will permit the use of short drills with an increase in drill rigidity and a decreased tendency for the drill to chatter and chip. Deep holes should be drilled using a sequential series (starting with the shortest) of drills, gun drills, or oil-feeding drills.

Drill geometry is probably the factor most affecting tool life and hole quality. Maximum tool lives are obtained when the drills are uniformly ground with no local differences in geometry and without thermal damage (Ref. 25). The helix angle of the drills is dependent upon the alloy being machined. However, drills with helix angles typical of the regular heavy-duty drill types can be used for most drilling applications (Ref. 28). Small relief angles can cause excessive metal pickup, while large relief angles weaken the cutting edge. Successful use has been made of drills with relief angles between 3 and 15 degrees (Refs. 25, 30). The point angle of the drill is determined by the feed, drill size, and workpiece (Ref. 5). Generally, the larger relief angles are used with the sharper point angles (90 to 118 degrees). The flatter point angle drills (130 to 140 degrees) use lower relief angles that tend to have smaller thrust forces and that provide good support in the critical chisel-edge area.

Special point shapes have been developed to reduce work hardening of the metal at the bottom of the hole just ahead of the cutting edges. Crankshaft, notch-type, and split points with positive rake notching have all given good performance (Refs. 25, 29). Webs that have been thinned reduce the drilling pressure (Ref. 31) with no alteration in the effective rake angle.

Care must be taken to ensure that the recommended (or specified) drill geometry is being used. If necessary, drills should be accurately reground on a drill grinder; they should never be sharpened by hand. The drill geometry should be held concentric with the drill centerline. Uneven geometry results in uneven chip formation, drill deflection, out-of-round holes, and early tool failure. When drills are reconditioned, the entire drill should be treated to ensure conformance with the original drill geometry.

Machine-ground points with good finishes give good tool life (Ref. 32). Chromium plating or black-oxide coating of the flutes minimizes chips welding to the tool, and this improves tool life.

Cutting Conditions. Low speeds should be used during the drilling of nickel and nickel-base alloys. Speeds should range to 75 feet per minute for pure nickel while 10 to 20 fpm should be used for materials such as René 41 and Udimet 700 (Refs. 28, 29). Lower speeds should be used for deep holes to compensate for poor lubrication and cooling (Ref. 25).

Hand drilling should be avoided whenever possible. The drill should always be kept cutting during drilling of nickel-base alloys. Riding in the hole without cutting rapidly work hardens the workpiece, galls the tool lips, and dulls the drill. The high axial thrust necessary to cut efficiently nickel-base alloys, particularly when solution treated and aged, can cause rapid operator fatigue. Moreover, on breadthrough, the rapid advance common to hand drilling results in extensive chipping and dulling of the drill corners. A feed range from 0.0005 to 0.004 inch per revolution (ipr) is used for drills up to 1/4-inch diameter. A heavier feed is used for larger drills.

Cutting fluids with good lubricating and antiweld properties are desirable for machining nickel-base alloys (Ref. 29). Lubricating and chemically active chlorinated and sulfochlorinated cutting oils are recommended (Ref. 25, 29). Sulfochlorinated fluids are generally preferred, although the work must be thoroughly cleaned to remove all traces of sulfur. Otherwise, severe intergranular corrosion by the sulfur, particularly at high temperatures, could result. Holes over 2 diameters deep generally require oil-feeding drills to maintain adequate lubrication.

Drilling Procedure. When the drilling operation is started, the drill should be at the operating speed and under positive feed. The drill point should be sharp. A triangular center punch should be used to mark the center of the hole instead of a circular punch (Ref. 5). The drill margin should be periodically inspected for smearing or lip breakdowns. Establishment of regular drill replacement will prevent work and drill scrapping. The drill should be periodically removed from the work to free chips from the tool unless fluid flow is sufficient. The drill should be retracted and re-engaged quickly to prevent dwelling. Prior to breakthrough, the drill should be withdrawn and the hole and tool freed of chips. The breakthrough is then made under positive feed with care to avoid "feed surge" at breakthrough (Ref. 5). Drilled holes generally must be reamed if close tolerances are required.

Trepanning. A unique method has been developed for producing trepanned holes from 1/4- to 2-inch diameter in precipitation-hardened René 41 0.020 to 0.0625 inch thick (Ref. 33). Figure 23 shows the two-tooth-cutter geometry used for this operation. The cutter operates at 50 rpm and 0.007 ipr feed. Once-through, close-tolerance holes have been produced using two-tooth cutters with a peripheral reaming surface.

Reaming. Reaming of drilled holes results in close-tolerance holes with a good finish. Reaming, like all other machining operations, must be done with the proper tools and conditions.

Reaming Tools. Fluted reamers are available as standard tools for use with nickel-base tools. These reamers have right-hand cuts and positive axial and rake angles (Ref. 31). Spiral-fluted reamers provide smoother cutting action and less chattering than straight-fluted reamers. However, when extreme accuracy is required, straight-fluted reamers are usually preferred (Ref. 5).

Reamers should be as short as possible to obtain maximum tool rigidity and better hole tolerances. The chamfer and rake angles of a reamer do not have any pronounced effect upon reaming. The relief angle is critical and should range between 5 and 10 degrees to avoid smearing (with too low an angle) and chattering (with too high an angle). The reamer margin is generally wider than 0.005 inch to prevent chatter, but no wider than 0.010 inch to prevent scoring. High-speed tool-steel reamers can be used satisfactorily with nickel-base alloys. Carbide-tipped reamers can operate at higher speeds with a much better tool life.

Cutting Conditions. Reaming should be done using a rigid setup, sharp tools, and proper speeds. The cutting speeds recommended for commercially pure nickel are 30 fpm for high-speed tool-steel reamers and 90 fpm for carbide-tipped reamers. Highly alloyed high-strength nickel-base alloys require lower cutting speeds – 10 to 25 fpm for high-speed tool steel reamers and 40 to 70 fpm for carbide-tipped reamers (Ref. 5). Low feeds from 0.002 to 0.020 ipr are used depending upon the reamer diameter and alloy (Refs. 31,34). Too low a feed produces glazing while an excessive feed reduces the dimensional accuracy and impairs the surface finish (Ref. 31). The

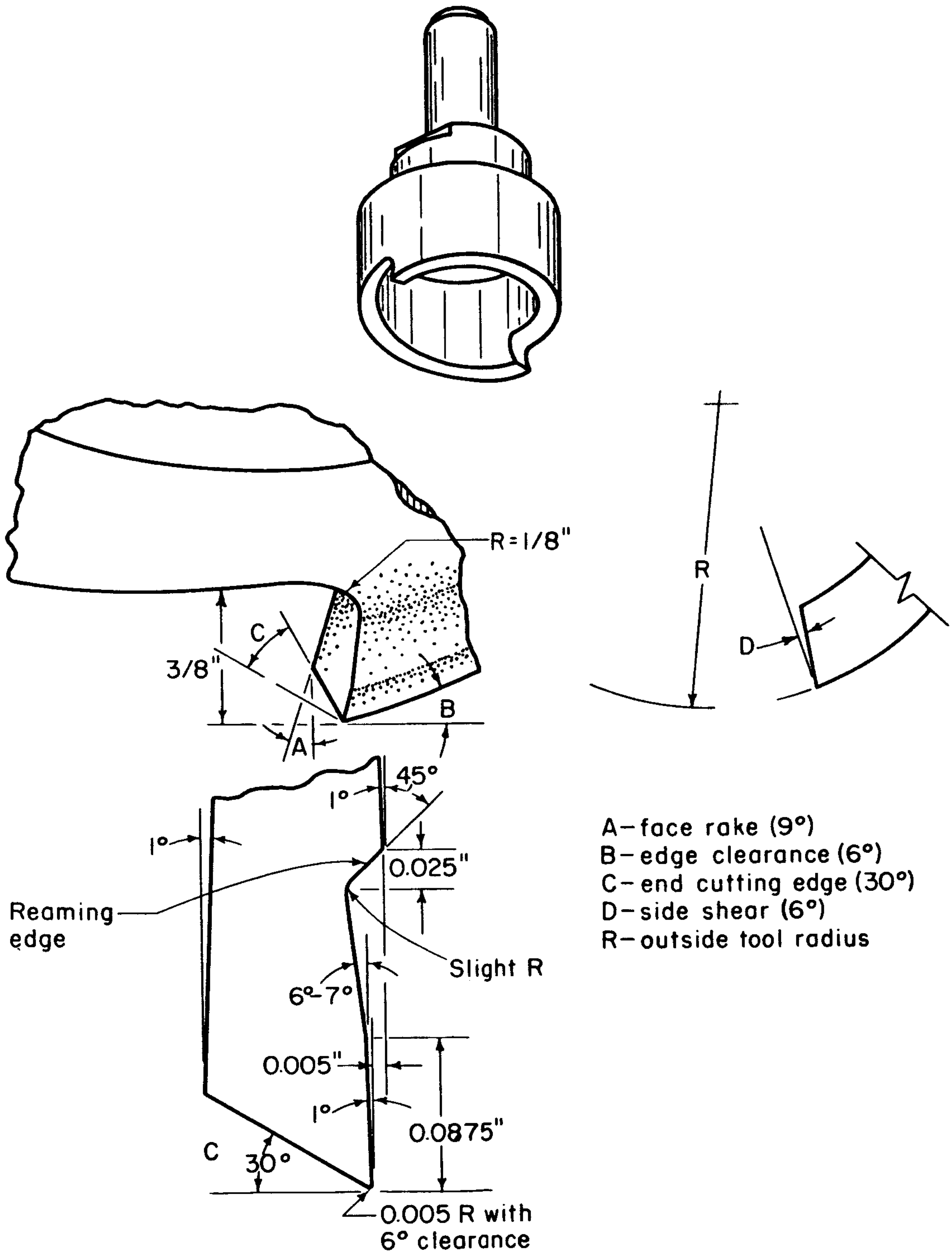


FIGURE 23. TREPANNING TOOL AND TOOTH FORM (REF. 33)

For use on René 41.

reaming operation should remove the material work hardened by the drill. The depth of cut ranges from about 0.010 inch for a 1/2-inch-diameter hole to 0.025 inch for a 1-1/2-inch-diameter hole (Ref. 31).

Chlorinated, sulfochlorinated, and highly sulfurized oils are the most effective lubricant coolants. Care must be taken to remove all traces of sulfur compounds on the nickel-base alloys prior to exposure to elevated temperatures.

Tapping. Tapping is a difficult machining operation to perform on nickel-base alloys. Poor chip flow and galling action result in excessive tap seizure, broken taps, poor fits, and rough threads. Nickel-base alloys tend to upset into the root of the tap; this causes seizing of the tap. Because of this upsetting (Ref. 35), a hole for a 75 per cent thread in nickel-base alloys will not allow re-entrance of the plug gage after tapping.

As the tap enters and the cutting temperature rises, the nickel-base alloys tend to weld on the cutting edges and flanks of the tap, resulting in oversized holes and rough threads. Galling also increases the torque requirements necessary to overcome the increased friction between the tap and the metal. The additional torque distorts the tap lead and increases the tapping stresses further until the tap seizes and breaks (Ref. 25).

Tapping problems are reduced by the use of a 50 to 60 per cent thread and by tapping the fewest number of threads possible (Ref. 35). Thread-strength tests have shown that thread heights above 60 per cent for the tapped member do not necessarily increase the strength of the threaded fastener (Ref. 5).

Designers should avoid specifying blind, tapped holes or tapped holes with a length exceeding 1-1/2 times the tap diameter. Relaxation of the class of fit tolerances might also be considered.

Tapping Machines. A lead-screw tapping machine should be used to insure proper lead and regulated torque so that a uniform hole and thread size results. A friction clutch should also be used to prevent tap breakage. An accurate, sensitive machine should be used that is operated by a skilled operator so that tap breakage is minimized.

Taps. In general, high-speed tool steels perform satisfactorily as taps for use with nickel-base alloys. Several types of taps have been used successfully with nickel-base alloys. A simple tool is a modified two-flute, spiral-point, plug-style H2 pitch diameter tap. The taps are modified by grinding away the threads behind the cutting edges to the minor diameter, but leaving full thread lands 0.015 inch wide backing up the cutting edges. Chip-driving spiral-point taps with interrupted threads and eccentric pitch diameter relief also have been used successfully (Ref. 36). Taps must be ground in a machine setup, not by hand (Refs. 25, 36). Care should be taken to ensure equal chip loads are present on all cutting edges during tapping; stress relieving after grinding is helpful.

Generally, taps with a minimum number of flutes are recommended. All taps should have a back taper of about 0.001 inch per inch of length (Ref. 36). Rubbing during tapping can be reduced by observing the following precautions in tap design (Refs. 25, 36):

(1) The bearing surface should be as narrow as possible

(2) The threads should be interrupted with alternate teeth missing

(3) The trailing edge of the tap should be ground away

(4) Axial grooves should be ground in thread crests along the full length of the land

(5) Eccentric or concentric thread relief should be employed.

Taps should be shaped to encourage good chip flow, to minimize seizure, and to provide good shearing action. A chamfer of three to five threads produces smaller chips and minimizes jamming of the tap as it is backed out.

Tapping Conditions. Tapping speeds range from 5 to 25 fpm, and care should be taken to avoid a critical tapping speed at which the torque abruptly increases. The tapping lubricant is very important because of galling. Highly chlorinated oils usually give the best results; a heavy sulfurized mineral oil is the next best (Refs. 37, 38). Molybdenum disulfide is a good lubricant to add when persistent galling occurs. Taps should be inspected periodically to detect any smears of metal on the lands, which indicate incipient tap failure. Tapping is generally a final machining operation and, therefore, errors in tapping are costly and can cause high scrap losses.

CLEANING OF JOINTS

Many forming operations of nickel-base alloys are conducted at elevated temperatures. The sensitivity of nickel-base alloys to embrittlement by sulfur or soft metals, as discussed in the section on corrosion, and the high-forming temperatures make a thorough cleaning imperative prior to forming. Mechanical cleaning of the surfaces (wire brushing, abrading, etc.) does not clean nickel-base alloys satisfactorily (Ref. 10). Five forms of surface contamination that may be present on nickel-base alloys are (Ref. 10):

(1) Solvent-soluble impurities: code paints, marking inks, greases, oils

(2) Water-soluble impurities: marking inks, salts, penetrant developers

(3) Metallic contaminants: metal picked up from soft tools, dies, and jigs made of lead, aluminum, zinc, etc.

(4) Thermal-treatment scale: oxides of chromium, nickel, cobalt, etc., formed during solution annealing and aging in air

(5) Mill scale: rolled in impurities in as-received materials.

Alkaline cleaning thoroughly removes water-soluble contaminants. Vapor degreasing removes most solvent-soluble contaminants thoroughly and readily. An alkaline bath composed of 6 to 7 ounces of phosphosilicate to 1 gallon of water at 180 F gives adequate cleaning results on René 41 and Hastelloy X (Ref. 23). Scale conditioning has been done in baths of alkaline permanganate solution that react with the scale to form soluble oxides. Immersion periods from 30 to 90 minutes are recommended (Ref. 23).

Neither nitric acid nor hydrofluoric acid used alone remove scale from nickel-base alloys. When the two are combined, a very effective solution for scale removal results. Most probably the scale is loosened by attack of the base metal under the scale. Mechanical abrasion of the surface after pickling can remove scale that was loosened during immersion in the acid bath, but that did not come off in the bath. A 35 per cent hydrofluoric-5 per cent nitric solution at room temperature reportedly was superior to a 20 per cent nitric-4 per cent hydrofluoric acid solution at 130 F (Ref. 23). Nitric-hydrofluoric-acid pickling of aged René 41 is not recommended because of the danger of excessive intergranular attack (Ref. 23). White-glove handling of the piece after cleaning avoids recontamination of the alloys.

ASSEMBLY OF JOINTS

The assembly procedures for mechanically fastened joints utilizing nickel-base alloys are similar to those used for fastening aluminum or steel alloys except for the handling techniques. The maintenance of contaminant-free fabrication facilities is mandatory for critical applications. The entire assembly should be kept clean and free of harmful contaminants. Drilling holes in pieces that are fitted up in a jig requires disassembly and deburring of the pieces before a fastener can be installed. The following sections briefly discuss methods of using several common fastening procedures.

Riveting. Riveting can be done in many ways, all being useful for a number of different applications. Rivets are installed either cold or hot. However, in most industrial applications, cold riveting is used because of the speed, efficiency, and elimination of potential thermal damage to rivet and parts.

An old and still common method of setting rivets is with a rivet set and impact hammer. The important precautions are to use the proper size of rivet set, to use the proper length rivet, and to prevent battering of the parts being joined by set or backup.

Squeeze riveting is done by applying a steady force to both ends of the rivet. This type of riveting lends itself to more precise control than impact upsetting. Battering of the parts being joined is avoided. Squeezed rivets do not have an upset head. The rivet is bulged out to form a cylinder larger in diameter than the hole. This method of riveting is more tolerant of out-of-size holes and mismatching of holes than other methods of setting rivets.

If a head is required and impact riveting should be avoided, spin riveting can be used. Spin riveting produces a head on the rivet by rotating a tool against the rivet while the rivet is held still. Clamping pressure of the rivet is controlled by the upsetting parameters. This riveting method permits setting a rivet with no residual clamping pressure. This leaves the parts free to rotate around the rivet.

Bolting. An important factor influencing the strength of a bolted joint is the amount of pretensioning in the bolt. Consequently, it is necessary to produce the proper tension in the bolt during assembly. This is done by being sure that the proper torque is achieved during tightening. Bolts are tightened by:

(1) Turn-of-nut method. The nut is turned to a predetermined tightness (fingertight) then given a specified amount of turn. The method is simple but not very accurate in producing a given pretension.

(2) Manual torque wrenching. A torque wrench has a dial that indicates the torque being applied. The nut is tightened to some preselected torque. It is accurate but not fast.

(3) Pneumatic-impact wrench. Torque is controlled either by air pressure or by a cutoff. When air-pressure control is used the wrench stalls at the desired torque. The cutoff tool shuts off the air at the desired torque.

About 90 per cent of the torque applied during tightening is used to overcome friction. The balance produces tension in the bolt. With nickel-base fasteners, the torque requirements for overcoming friction can be even greater. Actual torque values for critical applications must be reached by experimentation.

CONCLUSIONS AND RECOMMENDATIONS

The state of the art of mechanical fastening of nickel-base alloys is not well defined or complete. Past research has focussed primarily on fastener-production methods or the basic mechanical properties of individual fasteners or simple joints. Discussion of the design, fabrication, use, and properties of mechanically fastened joints is so rare in the literature that either the mechanical fastening of nickel-base alloys is understood or it has not been widely studied. Specific steps should be taken to recognize mechanical fastening as a specific area of technology and to determine the properties of nickel-base joints:

(1) All future Government reports should include the key words of fastener or mechanical fastening even when only a small amount of data is presented.

(2) Unpublished data from Government programs and contractors that are related to fasteners or mechanical fastening should be collected, correlated, and published.

(3) Galling of nickel-base fasteners at elevated temperatures and subjected to cyclical loading should be studied in more detail to resolve presently contradictory data. An effort should be made to develop or evaluate coatings or lubricants for use at elevated temperatures.

(4) A study should be initiated with the objective of specifying simple, reproducible tests that will indicate the properties of fasteners and joints in service. Tests should determine such properties as ultimate tensile strength, yield strength, elongation, relaxation, coefficient of thermal expansion, modulus of elasticity, effects of bolt misalignment, and torquing values all versus time or temperature, or both.

APPENDIX

FASTENER TYPES

APPENDIX

FASTENER TYPES

Mechanical fasteners come in a wide variety of forms, shapes, and sizes. It has been estimated that there are more than 500,000 fastener items that can be identified by name, type, size, and material. The best place to obtain fastener data is from fastener manufacturers. The following lists a number of types of fasteners:

- Rivets: Large and small solid
  - Split or tubular
  - Blind
- Bolts
- Screws: Machine
  - Tapping
  - Set
- Snap fasteners
- Spring clips
- Staples
- Studs
- Pin fasteners
- Nails
- Nuts: Standard
  - Locking
  - Captive or self-retaining
- Washers
- Retaining rings
- Quick operating fasteners.

The list is taken primarily from The Fasteners Book issue of Machine Design (Ref. 1). As can be seen, a discussion of the types and uses of all of the fasteners mentioned would require a discussion beyond the scope of this report. Detailed discussions can be found in the Fastener Issues of Machine Design. Following are brief discussions of a number of fasteners which the authors hope will help in preliminary selection of methods of making mechanically fastened joints. This material has been abstracted from fastener issues of Machine Design (Ref. 1). These fasteners are used with common engineering materials and may also be used in the mechanical fastening of nickel-base alloys.

RIVETS

Rivets are generally low in unit and assembly cost, simple, and reliable. These factors make them popular for permanently fastened joints. Rivets can be divided into solid rivets, tubular and split rivets, and blind rivets.

Figure 24 shows the head styles available in standard solid rivets. Special head styles are also available. Large rivets are available in steel; small rivets are available in a variety of materials including steel, aluminum, brass, Monel, copper, and nickel.

Figure 25 shows basic designs for small tubular and split rivets. These rivets are not tension fasteners. However, in compressive and shear loading, they are the equivalent of solid rivets.

Figure 26 shows the basic types of blind rivets available. Two general types are available. In one, the upset is obtained by pulling or pushing a stem through or into a tubular rivet. The stem is available from the open side of the joint. In the second type, upsetting is produced by explosion of a change contained in a tubular or hollow rivet. The charge is ignited by applying heat to the rivet head on the open side of the joint. Some of the factors that should be considered when making joints with blind rivets are shown in Figure 27.

THREADED FASTENERS

More variety is available in threaded fasteners than in any other type of mechanical fastener. Threaded fasteners may be screws, bolts, or studs. Screws may be used with tapped holes or may be required to do the tapping. Bolts are fastened with a variety of nuts. Studs are used with pretapped holes and nuts.

Figure 28 shows the head styles available for threaded fasteners and gives a brief description of the head and use. Table VII describes the application of the Unified Thread Series for threaded fasteners. Table VIII shows the pitch-diameter combinations for the Unified Thread Series.

Standard bolt and screw styles are shown in Figure 29; Figure 30 shows standard nut styles. In addition to these standard types, innumberable head designs have been developed for special purposes. A wide variety of the locknuts have been developed and are available.

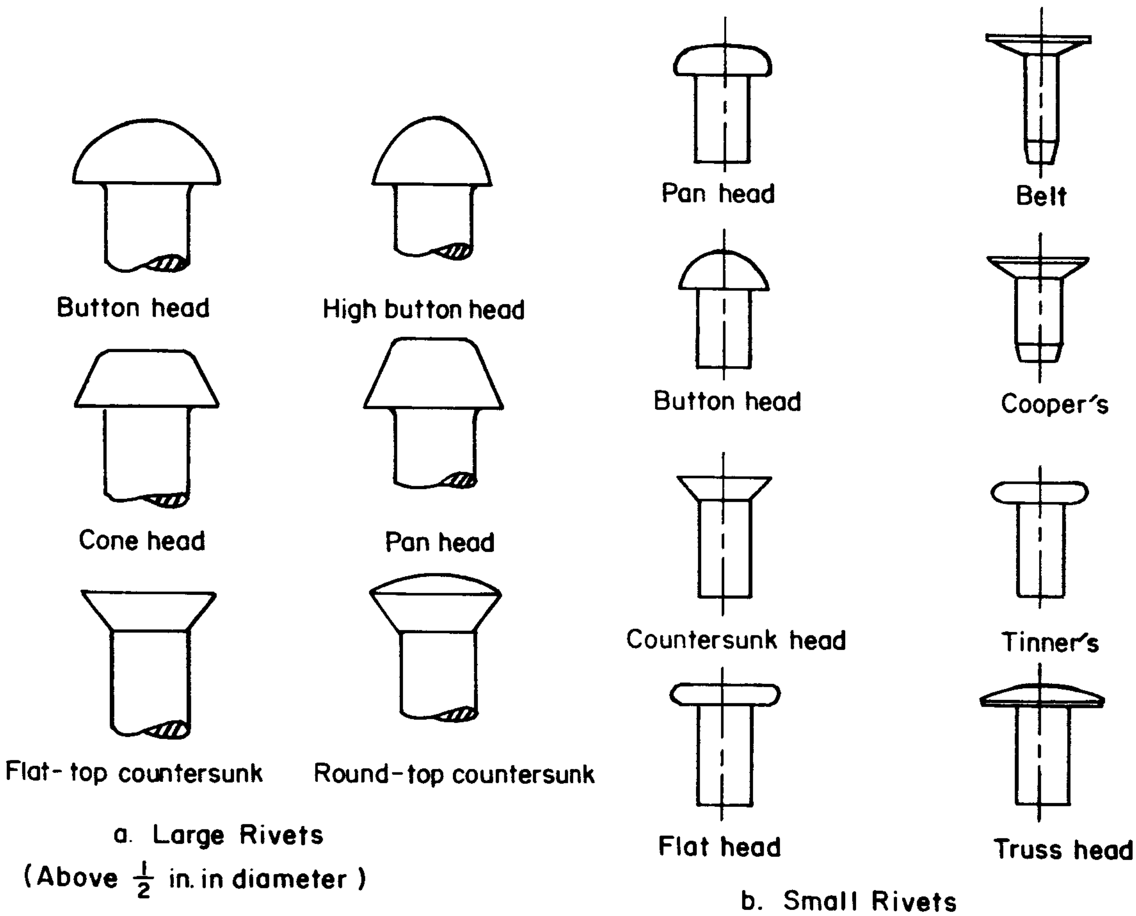
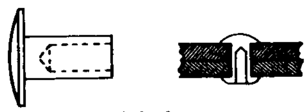
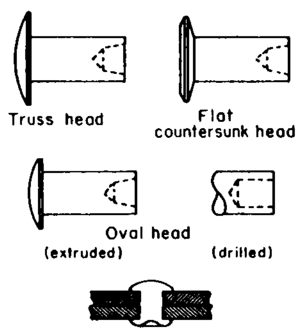


FIGURE 24. STANDARD SHAPES AVAILABLE IN SOLID RIVETS (REF. 1)



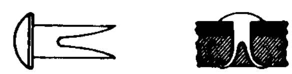
a. Tubular

Has a drilled shank with hole depth more than 112 per cent of mean shank diameter. Can be used to punch its own hole in fabric, some plastic sheet, and other soft materials, eliminating a preliminary punching or drilling operation. Shear strength is less than for a semitubular rivet.



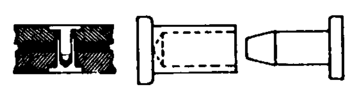
b. Semitubular

Most widely used type of small rivet. Depth of hole in rivet, measured along wall, does not exceed 112 per cent of mean shank diameter. Hole may be extruded (straight or tapered) or drilled (straight), depending on manufacturer and/or rivet size. When properly specified and set in a prepared hole, this rivet becomes essentially a solid member since hole depth is just enough to form clinch. Used whenever maximum shear strength is needed. Strength in shear or compression is comparable to solid rivet. Dimensions have been standardized by Tubular and Split Rivet Council: Nominal body diameters, 0.061 to 0.310 in.; corresponding minimum lengths, 1/16 to 1/4 in.



c. Bifurcated (Split)

Rivet body is sawed or punched to produce a pronged shank that punches its own hole through fiber, wood, or plastic. With a few exceptions, punched shanks are more suitable than sawed shanks for piercing operations on nonmetallic materials. Sawed or broached types serve for applications in nonmetallic materials such as leather or fabric. Sawing or broaching does not distort leg as much as punching does, but punching cold works the material and makes it stronger. However, size of rivet may affect this general rule.



d. Compression

Consists of two elements: Solid or blank rivet and deep-drilled tubular member. Pressed together, these form an interference fit. Because heads of both members can be produced to close tolerances, these rivets are commonly used when appearance from both sides of the work must be uniform and heads must be flush to prevent accumulation of dirt or waste. Can be used in wood, brittle plastics, or other materials with little danger of splitting during setting.

FIGURE 25. BASIC TYPES OF SMALL RIVETS OTHER THAN SOLID (REF. 1)

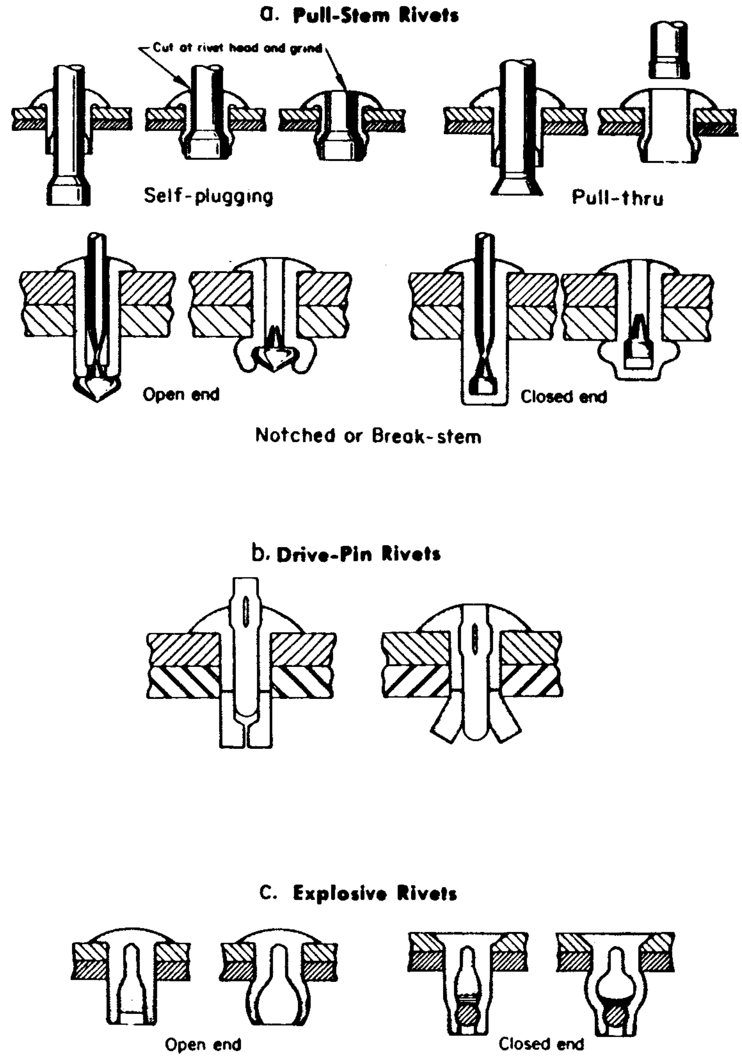
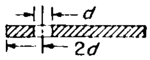
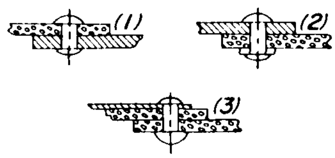


FIGURE 26. BASIC BLIND-RIVET TYPES AND METHODS OF SETTING (REF. 1)



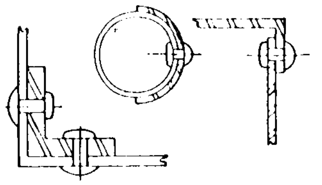
a. Edge Distance

Average recommended edge distance is two times the diameter of the rivet. In lightly loaded structures where the rivet performs only a holding function, this can be decreased to 1½ diameters, and in heavily loaded structures, it may be necessary to increase it to as much as 3 diameters to develop required joint strength.



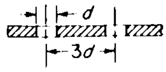
b. Rubber, Plastic and Fabric Joints

Some plastics, such as reinforced molded fibreglas or polystyrene, which are reasonably rigid, present no problem for most small rivets. However, when the material is very flexible or is a fabric, set the rivet as shown at (1) or (2) with the upset head against the solid member. If this practice is not possible, use a back-up strip as shown at (3)



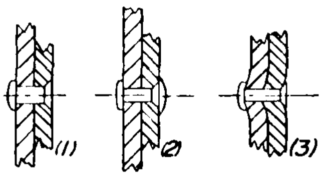
c. Sheet Metal

Some blind rivets are well adapted to assembly of sheet metal. Others which rely on shank deformation for holding action are not. If a choice can be made, it is always desirable to set the rivet against the thicker member. Backing it up with a washer or back-up strip in assemblies that are accessible from both sides is desirable for relatively thin sections, but not absolutely necessary.



g. Spacing

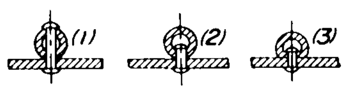
Rivet pitch should be three times the diameter of the rivet. Depending upon nature of load, it may be desirable to decrease or increase this distance. However, it is generally considered that 3 diameters overcome the tendency of the material to fail and concentrate the load on the rivet.



h. Flush Joints

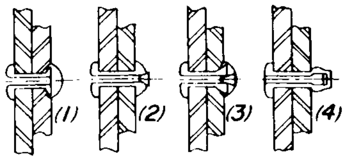
Generally, flush joints are made by countersinking one of the sections and using a rivet with a countersunk head, (1) Some rivets are available in either a round or a flat-top countersunk head, but not both. The rivet at (2) is capped.

Another popular method of providing flush assembly and gaining additional bearing strength is to dimple the sheet by forming a conical projection on the back of the sheets with a die. (3) A countersink-like recess is left on the front of the sheet which allows flush mounting of the rivet head. The projections in the two sheets are nested together to increase bearing strength.



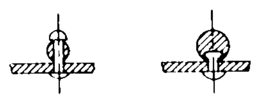
i. Attaching Tubing

Attaching tubing is an application for which the blind rivet is ideally suited. At (1), the rivet goes completely through the tubing. A very long rivet is required, but little advantage is obtained over the design shown at (2) where a shorter length is used. The design at (3) is recommended if the additional cost of milling or rolling the tubing with a flat on the surface is justified.



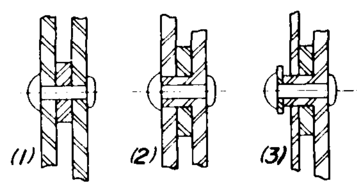
m. Weatherproof Joints

A hollow-core rivet can be sealed by capping it, (1) by plugging it, (2) or by using both a cap and a plug. (3) To obtain a true seal, however, a gasket or mastic should be used between the sections and perhaps under the rivet head. An ideal solution is to use a closed-end rivet. (4) Use of a covering seal is sometimes recommended, although this requires forming or cutting a channel in the parts to be assembled. Where weathertight tightness, but not pressure or moisture tightness, is desirable, the sections may simply be painted.



n. Attaching Solid Rod

In attaching a rod to other members, usual practice is to pass the rivet completely through the rod. If this is impractical, attachment can be made into a milled slot or drilled hole.

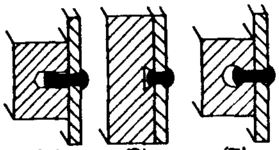


o. Pivoted Joints

There are a number of ways of producing a pivoted assembly, three of which are shown. Notice that the methods (2) and (3) prevent the clamping force of the rivet from influencing pivot movement.

Other acceptable methods of creating pivoted joints include: Use of backup strips; use of special nosepieces with the riveting tool; and selection of rivets made of softer alloys.

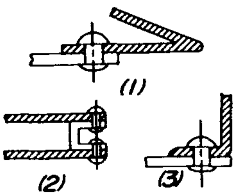
FIGURE 27. BLIND-RIVET-JOINT CONSIDERATIONS (REF. 1)



(1) (2) (3)

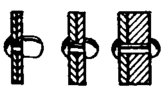
d. Blind Holes or Slots

A useful application of a blind rivet is in fastening members in a blind hole. At (1) the formed head bears against the side of the hole only. As could be expected, this joint is not as strong as the other two,(2) and (3) but *the clinching* action of the rivet head provides sufficient strength for light tension loads and moderate shear loads.



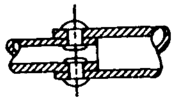
e. Clearance

An angular section is riveted to a straight member. (1) If the angle projects above the rivet head, it may be difficult to put *the tool* in to *upset* the rivet. One method of solving this problem is to pull the rivet from the underside of the work. In riveting the U-channel, (2) to the outer members, the rivet must be fed from the outer side. On this joint, allow enough back-up clearance to prevent interference. At (3) not only tool clearance, but also rivet head clearance is critical. A large diameter head may interfere with the wall.



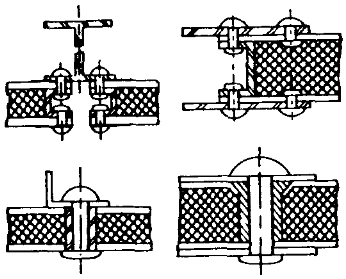
f. Length

Amount of length needed for clinching action varies greatly and depends on material being fastened, necessary strength, and method of riveting. Most rivet manufacturers provide data on grip ranges of their rivets to simplify selection for the user.



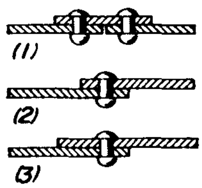
j. Joining Tubing

This tubing joint is a common form of blind riveting, used for both structural and low-cost power-transmission assemblies.



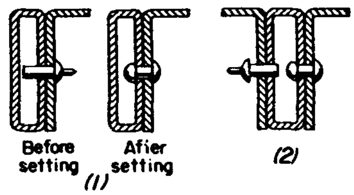
k. Honeycomb Sections

Inserts should be employed to strengthen the section and provide a strong joint. Otherwise, setting the rivet may deform the section and cause a structural weakness that may later result in failure.



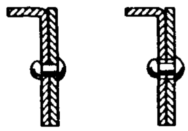
l. Riveted Joints

Riveted cleat or batten holds a butt joint. (1) Simple lap joint, (2) must have sufficient material beyond hole for strength. *Excessive material beyond rivet hole,*(3) may curl up, or vibrate, or cause interference problems depending on the installation. Best solution is to trim the panel to leave an edge about twice the hole diameter in width. Alternate solution would be to relocate the rivet at a position halfway between upper and lower panel edges.



p. Backup Clearance

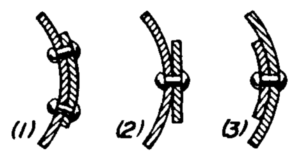
Full entry of the rivet is essential for tightly clinched joints. Sufficient backup clearance must be provided to accommodate the full length of the *unclinched* rivet, (1) In the case of two opposed rivets, the minimum allowable space accommodates one clinched and one unclinched rivet, (2)



(1) (2)

q. Hole Clearance

For vibration-proof construction or high shear strength, hole tolerances can be held very tight, (1) If it is possible to use rivets that depend on clamping action of the heads for holding power, economy can be achieved in machining and assembly by allowing generous clearance around the rivet body, (2).



r. Making Use of Pull Up

By judicious positioning of rivets and parts that are to be assembled with rivets, the setting force can sometimes be used to pull together unlike parts. Rivets pull flat cleat into close over-all juxtaposition to the curved surface at (1) and (3) but the rivet at (2) does little to help mold the parts together.

FIGURE 27. (CONTINUED)

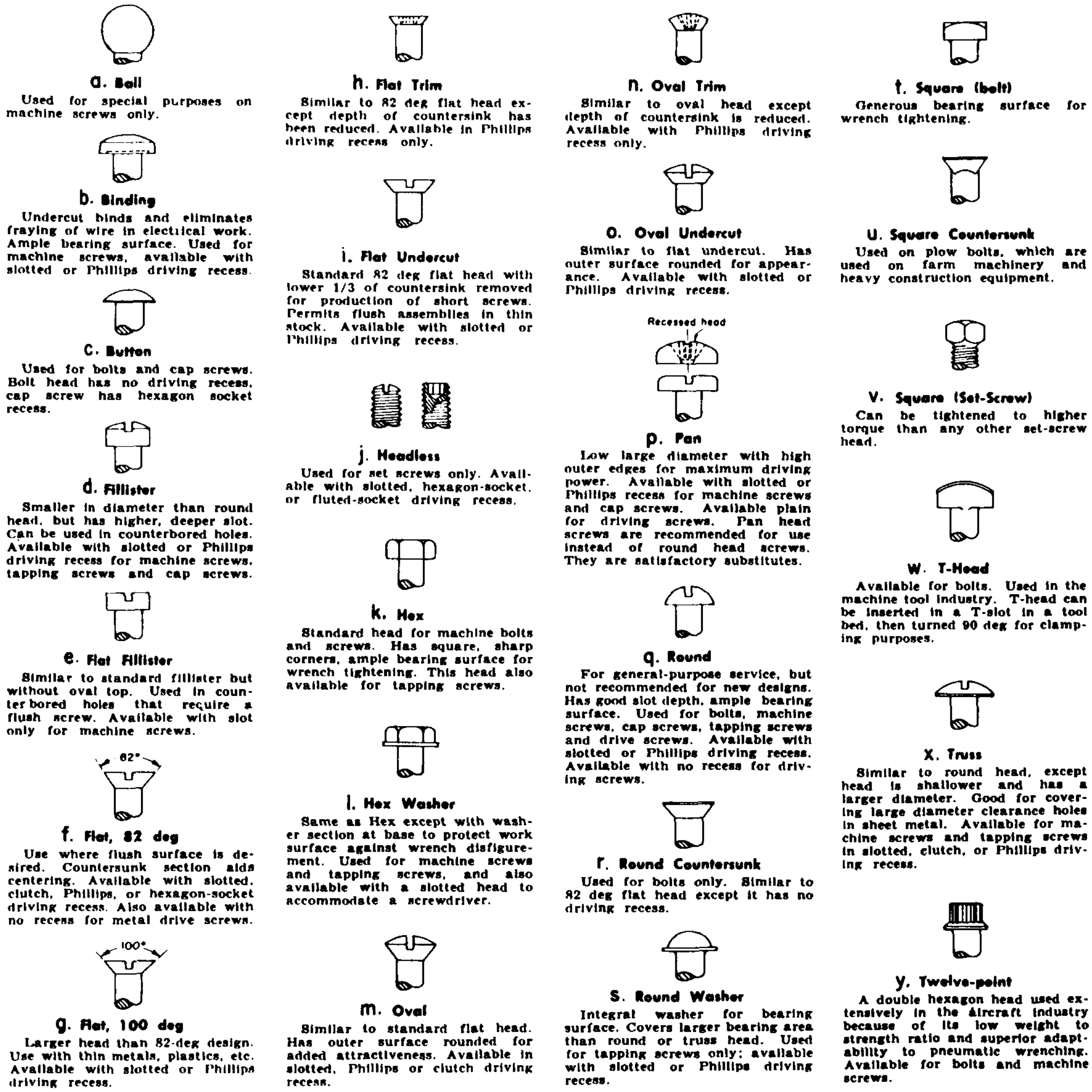


FIGURE 28. THREADED-FASTENER HEAD STYLES (REF. 1)

TABLE VII. APPLICATIONS OF UNIFIED THREAD SERIES (REF. 1)

Series	Application
Coarse-Thread (UNC)	Used for bolts, screws, nuts in all general engineering applications where conditions do not require a finer pitch thread. Areas of application include cast and malleable iron, soft metals, plastics and threaded parts that require rapid assembly or disassembly.
Fine-Thread Series (UNF)	Suitable for bolts, screws, nuts, and general applications where thread engagement is limited, or where other conditions such as thin walls may necessitate the use of a fine pitch. This series is normally not recommended for use in soft metals, plastics, etc.
Extra-Fine-Thread Series (UNEF)	Widely used in aircraft, missiles, and other aeronautical equipment where three requirements must be met: 1. Thin-wall material is to be threaded. 2. Thread depth of nuts and coupling flanges must be held to a minimum. 3. Maximum practicable number of threads is required within a given length of thread engagement.
4-Thread Series (4UN)	Uniform-pitch series. Basically, a continuation of the coarse-thread series in sizes over 4 in.
6-Thread Series (6UN)	Uniform-pitch series intermediate between 4 and 8 pitch series. Not a preferred series.
8-Thread Series (8UN)	Uniform-pitch series originally developed for high-pressure applications, such as bolts for high-pressure pipe flanges, cylinder-head studs, etc. Often used as a substitute for coarse-thread series in fastener diameters larger than 1 in.

TABLE VII. (Continued)

Series	Application
12-Thread Series (12UN)	Uniform-pitch series originally developed for use in boilers. It is now used for large-diameter fasteners that require medium-pitch threads. Most common application is thin nuts on shafts and sleeves in machine assemblies. Also serves as a continuation of the fine-thread series for fastener diameters larger than 1-1/2 in.
16-Thread Series (16UN)	Uniform-pitch series. Used for large-diameter fasteners that require fine-pitch threads. Common applications include retaining nuts and threaded adjusting collars. Also serves as a continuation of the extra-fine thread series for fastener diameters larger than 2 in.
20-Thread Series (20UN)	
28-Thread Series (28UN)	
32-Thread Series (32UN)	Uniform-pitch series which are used in highly special applications demanding extremely fine pitch threads. Not recommended for fasteners.

TABLE VIII. PITCH-DIAMETER COMBINATIONS FOR UNIFIED SCREW THREAD STANDARD SERIES (REF. 1)

Size Designation				Basic Major Diameter, in.	Series With Graded Pitches(a)			Series With Constant Pitches(a)							
Primary		Secondary					Extra								
No.	In.	No.	In.		Coarse UNC	Fine UNF	Fine UNEF	4UN	6UN	8UN	12UN	16UN	20UN	28UN	32UN
0				0.0600	...	80	...	...	...	...	...	...	...	...	...
		1		0.0730	64	72	...	...	...	...	...	...	...	...	...
2				0.0860	56	64	...	...	...	...	...	...	...	...	...
		3		0.0990	48	56	...	...	...	...	...	...	...	...	...
4				0.1120	40	48	...	...	...	...	...	...	...	...	...
5				0.1250	40	44	...	...	...	...	...	...	...	...	...
6				0.1380	32	40	...	...	...	...	...	...	...	...	UNC
8				0.1640	32	36	...	...	...	...	...	...	...	...	UNC
10				0.1900	24	32	...	...	...	...	...	...	...	...	UNF
		12		0.2160	24	28	32	...	...	...	...	...	...	UNF	UNEF
	1/4			0.2500	20	28	32	...	...	...	...	...	UNC	UNF	UNEF
	5/16			0.3125	18	24	32	...	...	...	...	...	20	28	UNEF
	3/8			0.3750	16	24	32	...	...	...	...	UNC	20	28	UNEF
	7/16			0.4375	14	20	28	...	...	...	...	16	UNF	UNEF	32
	1/2			0.5000	13	20	28	...	...	...	...	16	UNF	UNEF	32
	9/16			0.5625	12	18	24	...	...	...	UNC	16	20	28	32
	5/8			0.6250	11	18	24	...	...	...	12	16	20	28	32
			11/16	0.6875	...	...	24	...	...	...	12	16	20	28	32
	3/4			0.7500	10	16	20	...	...	...	12	UNF	UNEF	28	32
			13/16	0.8125	...	...	20	...	...	...	12	16	UNEF	28	32
	7/8			0.8750	9	14	20	...	...	...	12	16	UNEF	28	32
			15/16	0.9375	...	...	20	...	...	...	12	16	UNEF	28	32
				1.0000	8	12	20	...	...	UNC	UNF	16	UNEF	28	32
			1-1/16	1.0625	...	...	18	...	...	8	12	16	20	28	...
	1-1/8			1.1250	7	12	18	...	...	8	UNF	16	20	28	...
			1-3/16	1.1875	...	...	18	...	...	8	12	16	20	28	...
	1-1/4			1.2500	7	12	18	...	...	8	UNF	16	20	28	...
			1-5/16	1.3125	...	...	18	...	...	8	12	16	20	28	...
	1-3/8			1.3750	6	12	18	...	UNC	8	UNF	16	20	28	...
			1-7/16	1.4375	...	...	18	...	6	8	12	16	20	28	...
	1-1/2			1.5000	6	12	18	...	UNC	8	UNF	16	20	28	...
			1-9/16	1.5625	...	...	18	...	6	8	12	16	20	...	...
	1-5/8			1.6250	...	...	18	...	6	8	12	16	20	...	...
			1-11/16	1.6875	...	...	18	...	6	8	12	16	20	...	...
	1-3/4			1.7500	5	...	...	...	6	8	12	16	20	...	...
			1-13/16	1.8125	...	...	...	...	6	8	12	16	20	...	...

TABLE VIII. (Continued)

Size Designation				Basic Major Diameter, in.	Series With Graded Pitches[a]			Series With Constant Pitches[a]							
Primary		Secondary													
No.	In.	No.	In		Coarse UNC	Fine UNF	Extra Fine UNEF	4UN	6UN	8UN	12UN	16UN	20UN	28UN	32UN
	1-7/8			1.8750	...	...	...	...	6	8	12	16	20	...	...
			1-15/16	1.9375	...	...	...	...	6	8	12	16	20	...	...
	2			2.0000	4-1/2	...	...	...	6	8	12	16	20	...	...
			2-1/8	2.1250	...	...	...	...	6	8	12	16	20	...	...
	2-1/4			2.2500	4-1/2	...	...	...	6	8	12	16	20	...	...
			2-3/8	2.3750	...	...	...	...	6	8	12	16	20	...	...
	2-1/2			2.5000	4	...	...	UNC	6	8	12	16	20	...	...
			2-5/8	2.6250	...	...	...	4	6	8	12	16	20	...	...
	2-3/4			2.7500	4	...	...	UNC	6	8	12	16	20	...	...
			2-7/8	2.8750	...	...	...	4	6	8	12	16	20	...	...
	3			3.0000	4	...	...	UNC	6	8	12	16	20	...	...
			3-1/8	3.1250	...	...	...	4	6	8	12	16	...	...	...
	3-1/4			3.2500	4	...	...	UNC	6	8	12	16	...	...	...
			3-3/8	3.3750	...	...	...	4	6	8	12	16	...	...	...
	3-1/2			3.5000	4	...	...	UNC	6	8	12	16	...	...	...
			3-5/8	3.6250	...	...	...	4	6	8	12	16	...	...	...
	3-3/4			3.7500	4	...	...	UNC	6	8	12	16	...	...	...
			3-7/8	3.8750	...	...	...	4	6	8	12	16	...	...	...
	4			4.0000	4	...	...	UNC	6	8	12	16	...	...	...
			4-1/8	4.1250	...	...	...	4	6	8	12	16	...	...	...
	4-1/4			4.2500	...	...	...	4	6	8	12	16	...	...	...
			4-3/8	4.3750	...	...	...	4	6	8	12	16	...	...	...
	4-1/2			4.5000	...	...	...	4	6	8	12	16	...	...	...
			4-5/8	4.6250	...	...	...	4	6	8	12	16	...	...	...
	4-3/4			4.7500	...	...	...	4	6	8	12	16	...	...	...
			4-7/8	4.8750	...	...	...	4	6	8	12	16	...	...	...
	5			5.0000	...	...	...	4	6	8	12	16	...	...	...
			5-1/8	5.1250	...	...	...	4	6	8	12	16	...	...	...
	5-1/4			5.2500	...	...	...	4	6	8	12	16	...	...	...
			5-3/8	5.3750	...	...	...	4	6	8	12	16	...	...	...
	5-1/2			5.5000	...	...	...	4	6	8	12	16	...	...	...
			5-5/8	5.6250	...	...	...	4	6	8	12	16	...	...	...
	5-3/4			5.7500	...	...	...	4	6	8	12	16	...	...	...
			5-7/8	5.8750	...	...	...	4	6	8	12	16	...	...	...
	6			6.0000	...	...	...	4	6	8	12	16	...	...	...

(a) Graded and constant thread pitches are in threads per inch.

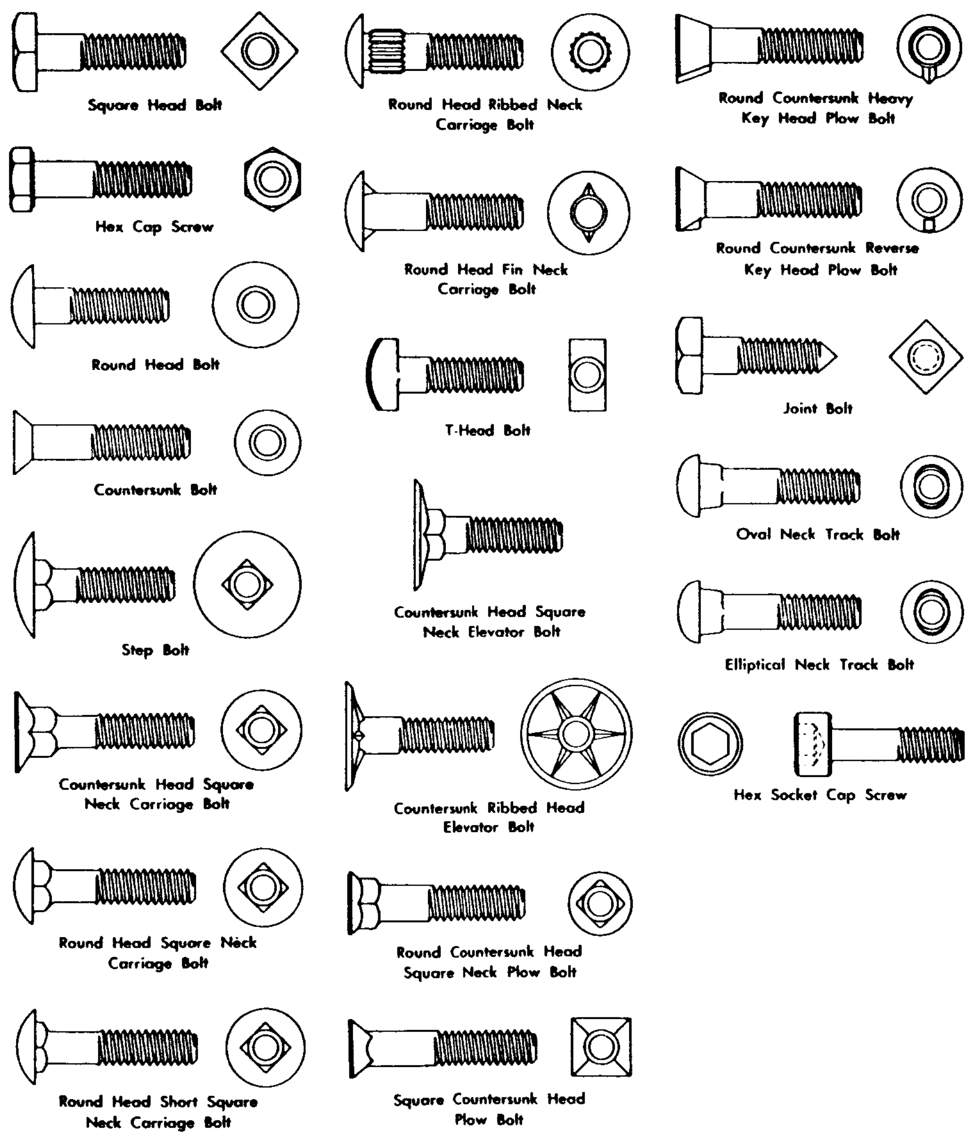


FIGURE 29. STANDARD BOLT AND SCREW STYLES (REF. 1)

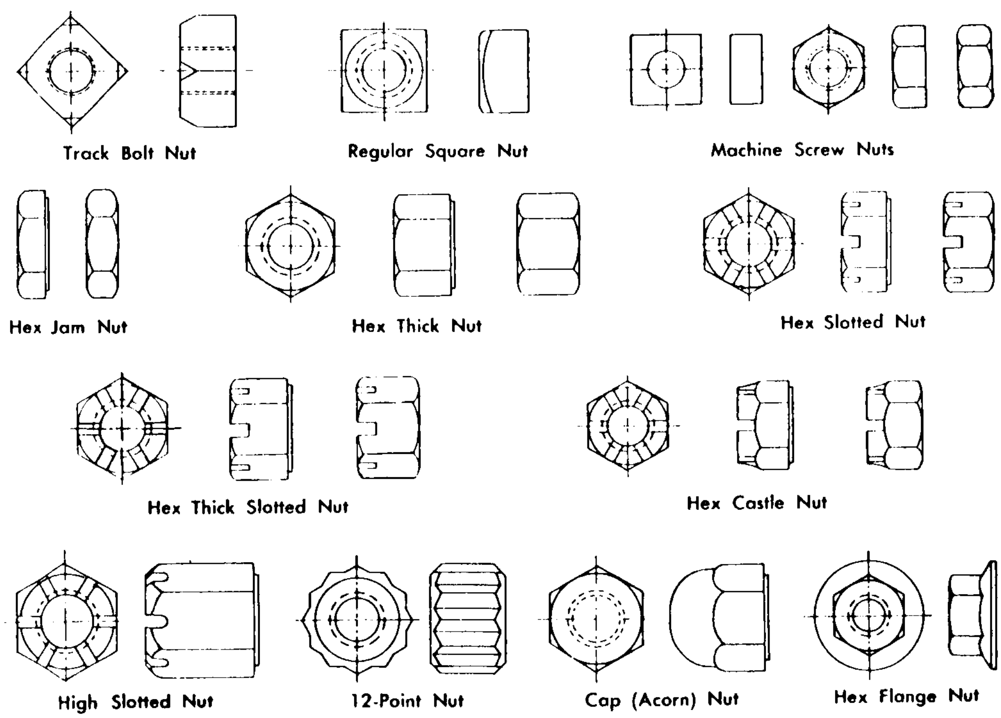
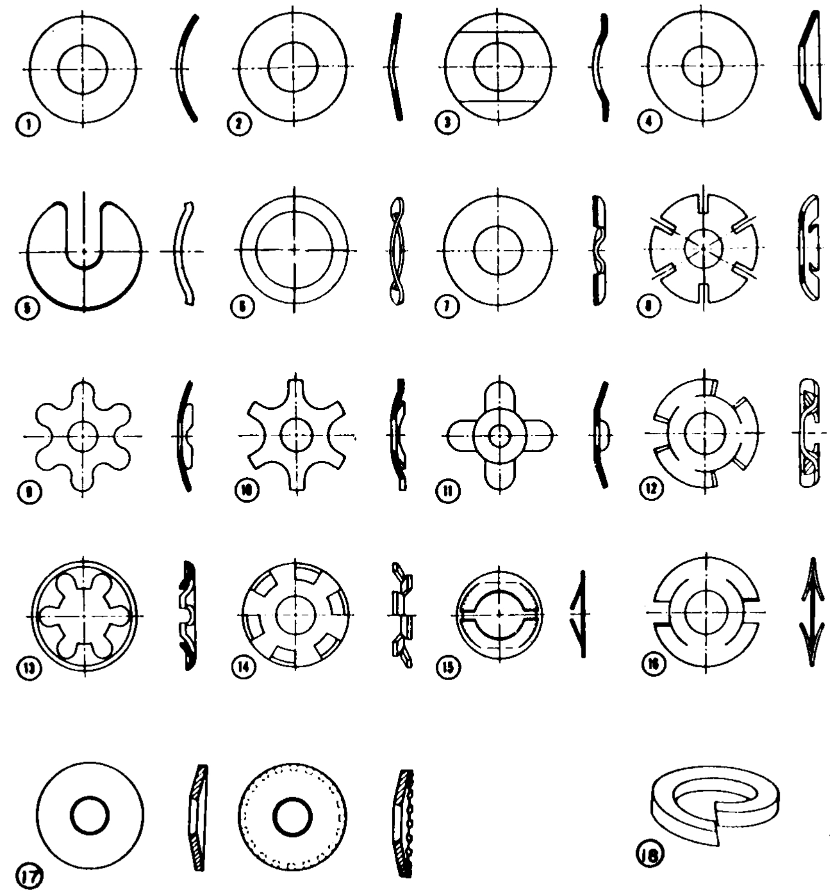


FIGURE 30. STANDARD NUT STYLES (REF. 1)

A locknut is a nut designed to grip the fastener or connected material in such a way as to prevent rotation of the nut in use. Dimensionally, locknuts are the same as standard nuts.

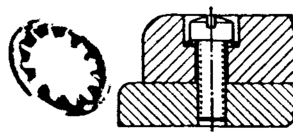
Washers are used with threaded fasteners for such diverse jobs as spanning an oversized hole, increasing bearing load, protecting surfaces from marring, and serving as locking devices for the fastener. Plain or flat washers are used for all of these functions except the last. Locking washers are designed to maintain tension loading on the fastener or to prevent rotation of the fastener after it is tightened. Figures 31 and 32 show a number of basic types of lock washers.

Tapping screws cut their own threads as they are driven into an untapped hole. The installation of tapping screws is economical since no tapping is required. They are made of case-hardened steel and have high strength. Therefore, they can stand a high driving torque and the screw is not likely to strip. However, care has to be taken to prevent stripping of the threads in the hole. They have been used in a wide variety of materials from plywood to stainless steel. Table IX shows the basic tapping-screw types.



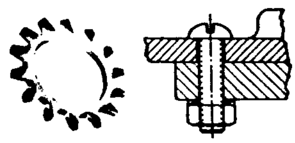
Type 1 is the basic design and most commonly used. It and Type 2 give greatest deflection, have smallest load-bearing surfaces. Type 3 gives less deflection but has greater load-bearing surface on one face. Type 4 is conical and gives still less deflection but stronger spring action. Type 5 slides into place in assembly. Types 6 and 7 have wave form. Type 6 has three waves, Type 7 four or more depending on size. These washers give minimum spring movement with high spring force and permit symmetrical load distribution because of multiple bearing points. Types 8 through 11 are special-purpose designs which provide for greater spring movement with uniform pressure distribution. Types 12 through 16 are also special-purpose types. Type 12 is used for preloaded ball bearings, primarily on electric motors. Types 13 and 14 have modified tooth arrangements, and Types 15 and 16 give maximum spring movement. Type 17 gives two examples of cone washers. Type 18 is a plain helical washer.

FIGURE 31. SPRING-WASHER DESIGNS (REF. 1)



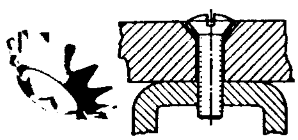
a. Internal

Used where projection of teeth beyond screw head or nut is objectionable. Presents a finished appearance, similar to plain washer. Standard sizes from No. 2 to 1¼ in. Up to 2¾ in. available. Heavy washer made in ¼ in. to ⅜ in. sizes.



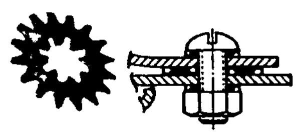
b. External

Most commonly used where security of assembly is critical. Teeth bite into standard screw heads and nuts to lock. Standard sizes from No. 3 to 1 in. Up to 2¼ in. available.



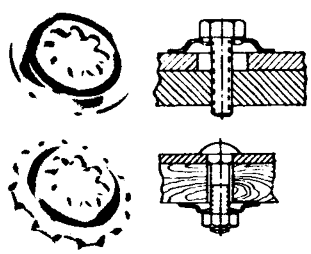
c. Countersunk

Used under countersunk screw heads. Standard sizes from No. 2 to ½ in. for 82 and 100 deg head styles.



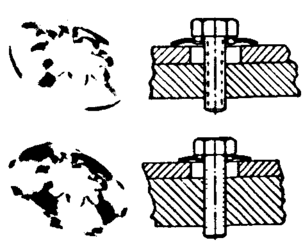
d. External-Internal

Cover oversize holes. Often used against soft materials and thin sheet steel because of large bearing surface. Can be used between two members which require adjustment before tightening. Resist rotation and sliding movements in final assembly. Can also be used for electrical bonding since teeth penetrate metal coatings to provide ground. Standard sizes from No. 4 to ⅝ in.



e. Dome Type

Recommended for use on soft or thin materials. Also suitable for use over large or elongated clearance holes. Plain-periphery type will not mar workpiece. Tooth-periphery type bites into workpiece and prohibits shifting. Standard sizes from No. 10 to ⅝ in.



f. Dished Type

Covers large bearing surface. Recommended for same general applications as dome type but where resilience rather than rigidity is required. Standard sizes from No. 4 to ½ in.

FIGURE 32. TOOTHED-LOCKWASHER DESIGNS (REF. 1)

TABLE IX. BASIC TAPPING-SCREW TYPES (REF. 1)

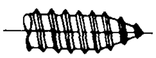
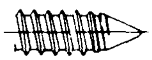
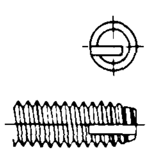
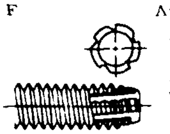
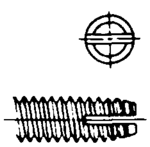
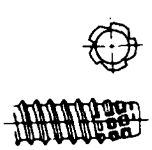
ASA Type and Thread Form	Description and Recommendations	Screw Sizes and Lengths: Screw Size	Length, in.	Screw Size	Length, in.
AB 	Spaced thread with same pitches as Type B and with gimlet point. Primarily designed for use in sheet metal, resin impregnated plywood, wood, and asbestos compositions. Used in pierced or punched holes where a sharp point for starting is needed. Use No. 6 screw for thin sheets up to and including 20 gage, and larger screw sizes up to 18 gage. Joint strength of easily deformed materials can be increased by using pilot holes less than root diameter of screw. Recommended hole sizes are the same as for Type B. Fast driving.	2	1/8 - 3/8	12	3/8 - 1-1/2
		4	3/16 - 3/4	14	3/8 - 3
		6	3/16 - 1	16	9/16 - 2
		7	1/4 - 1	18	5/8 - 2-1/4
		8	1/4 - 1-1/2	20	11/16 - 2-1/2
		10	1/4 - 2	24	3/4 - 2-1/2
B 	Type B is a blunt point spaced-thread screw. Can be used in heavy gage sheet metal and nonferrous castings. Used in assembling easily deformed materials where pilot hole is larger than root diameter of screw. Fast driving.	2	7/64 - 5/16	12	7/16 - 1-1/2
		4	3/16 - 1/2	1/4	1/2 - 2
		6	1/4 - 3/4	5/16	1/2 - 2-1/2
		7	5/16 - 1	3/8	1/2 - 2-1/2
		8	5/16 - 1	7/16	5/8 - 3
BP 	Type BP is same as Type B, but has a 45 deg included angle unthreaded cone point. Used for locating and aligning holes or piercing soft materials.	10	3/8 - 1-1/2	1/2	5/8 - 3
C 	Blunt point with threads approximating machine screw threads. For applications where a machine screw thread is preferable to the spaced thread form. Unlike thread cutting screws, the Type-C makes a chip-free assembly. In specific applications this screw may require extremely high driving torques due to long thread engagement or its use in hard materials. Resists loosening by vibration since greater engaged thread surface increases frictional resistance to backing out. Smaller helix angle of Type C provides tighter clamping action than Types A or B for equivalent driving torques.	2	1/8 - 3/8		
		4	3/16 - 1/2		
		6	3/16 - 3/4		
		8	3/16 - 3/4		
		10	1/4 - 1		
		12	5/16 - 1-1/2		
		1/4	3/8 - 1-1/2		
		5/16	3/8 - 1-1/2		
		3/8	1/2 - 2		
U 	Multiple threaded drive screw with steep helix angle and a blunt, unthreaded, starting pilot. Intended for making permanent fastenings in metals and plastics. Type-U screws are hammered or mechanically forced into the work, and should not be used in materials less than one screw diameter thick.	00	1/8 - 3/8	7	5/16 - 1/2
		0	1/8 - 3/8	8	3/8 - 5/8
		2	1/8 - 3/8	10	3/8 - 5/8
		4	3/16 - 5/16	12	1/2 - 3/4
		6	1/4 - 3/8	14	1/2 - 3/4
D 	Blunt point with single narrow flute and threads approximating machine screw threads. Flute is designed to produce a cutting edge which is radial to screw center. Requires less driving torque than Type-C screw and has longer length of thread engagement. Good for low-strength metals and plastics; for high-strength brittle metals; and for rethreading clogged pretapped holes. Easy starting, and gives highest clamping force for a given torque of any tapping screw.	2-56	3/16 - 1/2	8-36	5/16 - 1-3/8
		2-64	3/16 - 1/2	10-24	3/8 - 1-1/2
		3-48	1/4 - 1/2	10-32	3/8 - 1-1/2
		3-56	1/4 - 1/2	12-24	7/16 - 1-3/4
		4-40	1/4 - 3/4	12-28	7/16 - 1-3/4
		4-48	1/4 - 3/4	1/4-20	7/16 - 2
		5-40	5/16 - 3/4	1/4 - 28	7/16 - 2
		5-44	5/16 - 3/4	5/16 - 18	1/2 - 2-1/4
		6-32	5/16 - 1-1/4	5/16 - 24	1/2 - 2-1/4
		6-40	5/16 - 1-1/4	3/8 - 16	9/16 - 2-1/2
		8-32	5/16 - 1-3/8	3/8 - 24	9/16 - 2-1/2

TABLE IX. (Continued)

ASA Type and Thread Form	Description and Recommendations	Screw Sizes and Lengths			
		Screw Size	Length, in.	Screw Size	Length, in.
F 	Approximate machine screw thread and blunt point. Tapered thread may be complete or incomplete. Has 5 evenly spaced cutting grooves and large chip cavities. Used in a wide range of materials. Fast driving and resists vibration.	2-56 4-40 6-32 8-32	1/8 - 3/8 3/16 - 1/2 3/16 - 1 1/4 - 1	10-24 10-32 1/4 - 20	5/16 - 1-1/2 5/16 - 1-1/2 3/8 - 1-1/2
G 	Approximate machine screw thread with single through slot which forms two cutting edges. Blunt point has incomplete tapered threads. Recommended for same general use as Type-C, but requires less driving torque. Has higher percentage of thread and longer thread engagement than Type-C screw. Good for low-strength metals and plastics.	4-40 4-48 5-40 5-44 6-32 6-40 8-32 8-36 10-24	3/16 - 3/4 3/16 - 3/4 3/16 - 3/4 3/16 - 3/4 1/4 - 1-1/4 3/16 - 1-1/4 1/4 - 1-3/8 1/4 - 1-3/8 5/16 - 1-1/2	10-32 12-24 12-28 1/4 - 20 1/4 - 28 5/16 - 18 5/16 - 24 3/8 - 16 3/8 - 24	1/4 - 1-1/2 5/16 - 1-3/4 1/4 - 1-3/4 5/16 - 2 5/16 - 2 3/8 - 2-1/4 5/16 - 2-1/4 7/16 - 2-1/2 5/16 - 2-1/2
T 	Same as Type-D with single wide flute which provides more chip clearance. Cutting edge is right of the vertical center line of screw and provides an acute cutting edge which cuts easier than Type-D.	Same as Type-D except no 3/8 in. size.			
BF 	Spaced thread like Type-B screw, with blunt point and 5 evenly spaced cutting grooves and chip cavities. Cutting grooves remove only a small part of material, thus maintaining maximum shear strength in threaded hole wall. Wall thickness should be 1-1/2 times major diameter of screw. Reduces stripping in brittle plastics and die castings. Good for long thread engagement, especially in blind holes. Faster driving than fine thread types.	2 3 4 5 6 7	3/16 - 1/2 1/4 - 1/2 1/4 - 5/8 5/16 - 3/4 5/16 - 1 1/4 - 1	8 10 12 1/4 5/16 3/8	5/16 - 1-1/8 3/8 - 1-1/4 7/16 - 1-1/2 7/16 - 1-1/2 1/2 - 1-3/4 9/16 - 2
BT 	Same as Type-BF except for single wide flute which provides room for twisted, curly chips so that binding or reaming of hole is avoided.	Same as Type-BF.			

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MECHANICAL FASTENING OF NICKEL-BASE ALLOYS

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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